PB83-233676

Response of Skinner Lake (Indiana) to Agricultural Drainage

Michigan State Univ., East Lansing

Prepared for

Corvallis Environmental Research Lab., OR

Jul 83

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-600/3-83-057		PB83-238676

4. TITLE AND SUBTITLE	5. REPORT DATE
Response of Skinner Lake (Indiana) to Agricultural Drainage	July 1983
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
C.D. McNabb, B.J. Premo, F.C. Payne, T.R. Batterson, J.R. Craig	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Department of Fisheries and Wildlife Michigan State University East Lansin, Michigan 48824	11. CONTRACT/GRANT NO. R805046
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Environmental Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Corvallis, Oregon 97333	final 1978-1982 14. SPONSORING AGENCY CODE EPA/600/02

15. SUPPLEMENTARY NOTES

Project Officer: Spencer A. Peterson (FTS 420-4794)

16. ABSTRACT

During 1976-1981, various land management practices were initiated on the agricultural watershed of Skinner Lake in Noble County, Indiana. Implementation of these practices was sponsored by the U.S. Clean Lakes Program. The objective was to reverse the process of eutrophication in Skinner Lake. Studies reported were conducted to evaluate the effectiveness of the program.

Land treatment practices implemented on the watershed were chosen from the data and experience gained from the nonpoint source pollution study of Black Creek in Allen County, Indiana. Practices included use of settling basins, conservation tillage, group tile mains, terraces, livestock exclusions, diversions, grassed waterways, and planting vegetation on critical erosion sites. The Skinner Lake project evaluation model was based on eutrophication models that have been developed in the literature over the past several decades.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release to public	unclassified	60
	20. SECURITY CLASS *(This page)* unclassified	22. PRICE

EPA Form 2220-1 (9-73)

PB83-233676

EPA-600/3-83-057
July 1983

RESPONSE OF SKINNER LAKE (INDIANA) TO AGRICULTURAL DRAINAGE

C. D. McNabb, B. J. Premo, F. C. Payne,
T. R. Batterson, and J. R. Craig
Department of Fisheries and Wildlife
Michigan State University
East Lansing, Michigan 48824

R805046

Project Officer

S. A. Peterson
Environmental Research Laboratory
U.S. Environmental Protection Agency
Corvallis, Oregon 97333

ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CORVALLIS, OREGON 97333

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

DISCLAIMER

Although the research described in this article has been funded in part by the U.S. Environmental Protection Agency through grant number R805046 to Michigan State University, it has not been subjected to the Agency's required peer and policy review and therefore does not necessarily reflect the views of the Agency and no official endorsement should be inferred.

ABSTRACT

During 1976-1981, various land management practices were initiated on the agricultural watershed of Skinner Lake in Noble County, Indiana. Implementation of these practices was sponsored by the U.S. Clean Lakes Program. The objective was to reverse the process of eutrophication in Skinner Lake. Studies reported were conducted to evaluate the effectiveness of the program.

Land treatment practices implemented on the watershed were chosen from the data and experience gained from the nonpoint source pollution study of Black Creek in Allen County, Indiana. Practices included use of settling basins, conservation tillage, group tile mains, terraces, livestock exclusions, diversions, grassed waterways, and planting vegetation on critical erosion sites.

The Skinner Lake project evaluation model was based on eutrophication models that have been developed in the literature over the past several decades.

This report was submitted in fulfillment of grant R805046 by Michigan State University under the partial sponsorship of the U.S. Environmental Protection Agency. This report covers a period from 1978 to 1982, and work was completed as of 1983.

CONTENTS

Introduction. 1

Description of Study Site 6

Methods 10

Results 17

Discussion. 27

Literature Cited. 36

Appendix I. 39

Appendix II 51

Introduction

During 1978-1981, various land management practices were put in place on the agricultural watershed of Skinner Lake in Noble County, Indiana. Implementation of these practices was sponsored by US EPA Clean Lakes Program. Supplementary funds were provided by US Department of Agriculture, Soil Conservation Service. Costs were shared by landowners in the watershed. The objective was to reverse the process of eutrophication in Skinner Lake. Studies reported here were conducted to evaluate the effectiveness of the program. These studies were funded under a Cooperative Research Grant from US EPA Environmental Research Laboratory-Corvallis from January, 1978 to December, 1981, with support from Noble County Soil and Water Conservation District from March, 1982 to July, 1982, and from the Michigan Agriculture Experiment Station through the last collection of field data in September, 1982.

The particular land treatment practices implemented on the watershed of Skinner Lake were chosen from the data and experience generated by the non-point-source pollution study of Black Creek in nearby Allen County, Indiana (Christensen and Wilson, 1979; Lake and Morrison, 1977). These included settling basins, conservation tillage, group tile mains, terraces, livestock exclusion, diversions, grassed waterways, and planting vegetation on critical erosion sites. The work accomplished is shown in Figure 1. The product of the evaluation studies was a model which described the quantitative relationship between phosphorus concentration in streams coming into the lake and algal biomass in the lake in the ice-free period of the year. Variables in the model were derived from measurements made on the system early in the implementation program; over an annual water cycle in 1978-1979. The accuracy of the model was tested in 1982, when data were collected on the assumption that land treatment would change the phosphorus concentration in streams entering the lake.

The Skinner Lake project evaluation model was based on eutrophication models that were developed in the literature over the past several decades. Sawyer (1947) was among the first to use the concept of nutrient loading in his studies of effects of agricultural and urban drainage on the fertility of the Madison, Wisconsin, lakes. He observed that lakes which received the greatest quantity of phosphorus and nitrogen experienced the most frequent

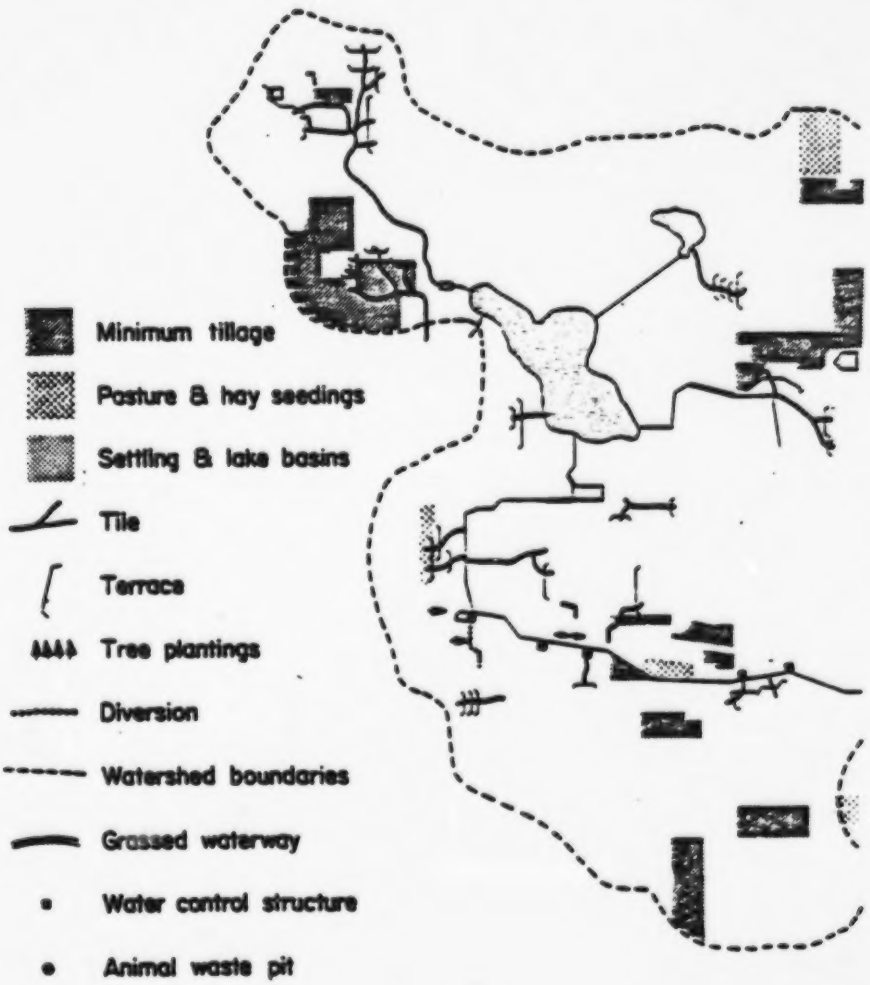

Figure 1(a). Land management practices applied to the west portion of of the Skinner Lake watershed during 1979-1981.

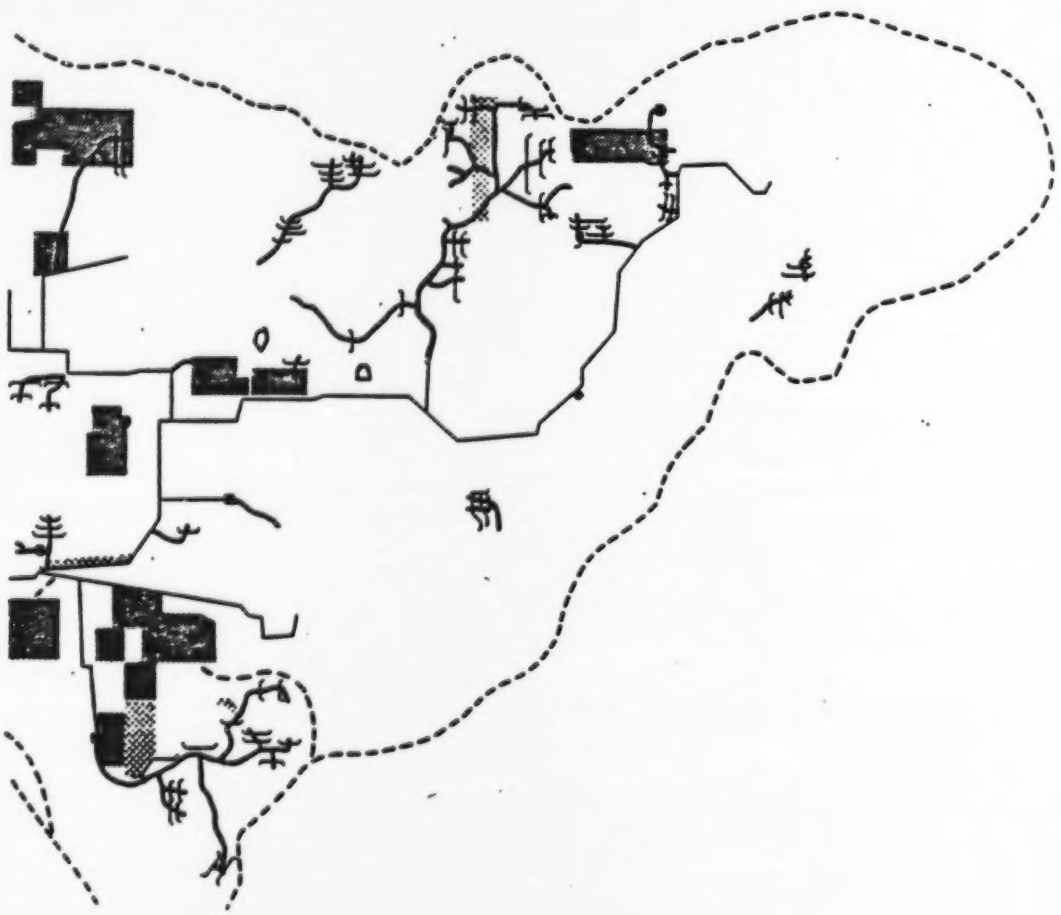

Figure 1(b). Land management practices applied to the east portion of the Skinner Lake watershed during 1979-1981.

and most severe algal blooms. Rawson (1955) and Edmondson (1961) emphasized the importance of mean depth to the productivity of water-bodies. This parameter took into account the degree of dilution of nutrients entering from the watershed. Vollenweider (1968) quantitatively defined the relationship between nutrient loading and planktonic algal response. This relationship showed that lakes of similar planktonic production had similar ratios of total phosphorus loading (mg P m^{-2} yr^{-1}) to mean depth. Dillon (1974, 1975) was the first to report water-bodies which did not fit Vollenweider's original phosphorus loading scheme. Dillon explained the anomolous fit of his lakes as due to their rapid flushing rates. Vollenweider (1975, 1976) pointed out that nitrogen limitation was known to occur in lakes, and such water-bodies would not be expected to fit his phosphorus loading models. Sakamoto (1966), Chiaudani and Vighi (1974), and Smith and Shapiro (1980) showed that examination of $[\overline{TN}]/[\overline{TP}]$ in the photic zone was a useful procedure for separating N-limited and P-limited systems. Their work predicted that if $[\overline{TN}]/[\overline{TP}]$ was greater than 10, algal production in the majority of lakes was likely phosphorus rather than nitrogen dependent.

In an attempt to allow for effects of fast or slow flushing rates and sedimentation of phosphorus on nutrient loading-trophic response relationships, Vollenweider (1975, 1976) modified his phosphorus loading model to include hydraulic residence time and phosphorus residence time. Based on the data from 200 lakes in 50 countries participating in the Organization for Economic Cooperation and Development (OECD) Cooperative Program on Lake Eutrophication, Vollenweider and Kerekes (1980) found that residence time of water and phosphorus in lakes were key factors and were related in the following manner:

$$t_p/t_w \propto \frac{[\overline{TP}_L]}{[\overline{TP}_i]} \cong \frac{1}{1 + t_w^{\frac{1}{2}}}$$

and

$$[\overline{TP}_L] \cong \frac{[\overline{TP}_i]}{1 + t_w^{\frac{1}{2}}} \qquad (1)$$

where t_p was the residence time of phosphorus, t_w was the hydraulic residence

time, $[\overline{TP}_i]$ was the mean incoming phosphorus concentration and $[\overline{TP}_L]$ was the mean lake phosphorus concentration. This relationship between a water-body's mean in-lake phosphorus concentration and incoming phosphorus concentration was the same as that developed by Larsen and Mercier (1976) and was similar to those developed by Kirchner and Dillon (1975), Chapra (1975), Reckhow (1977) and Walker (1977). From data of the OECD lakes, Vollenweider and Kerekes (1980) also presented a relationship between concentration of total phosphorus in a lake and algal production as measured by chlorophyll a concentration. The relationship was expressed as:

$$(2) \quad \log [\overline{\text{chl } a}] = 0.99 \log [\overline{TP}_L] - 0.57$$

where $[\overline{\text{chl } a}]$ was mean chlorophyll a concentration and $[\overline{TP}_L]$ was mean in-lake total phosphorus concentration. Since the time equations (1) and (2) were presented by Vollenweider and Kerekes (ibid.), a final report of the OECD project has been published (OECD, 1982). The constants in equations (1) and (2) were revised to fit the final data analysis of the project.

The OECD models were empirically derived from temperate zone lakes of varying water quality and productivity, and with widely differing flushing rates. These models represent a starting point for examining the relationships between phosphorus and chlorophyll a in specific phosphorus limited lakes. Because Skinner Lake was phosphorus limited in the sense of Sakamoto (1966) and Smith (1982), relationships in the OECD models were used as the basis for developing a model specific for the Skinner Lake system. This Skinner-specific model has been used here to put the degree of change in Skinner Lake in the post-implementation year of 1982 into perspective.

Description of Study Site

Skinner Lake has an average depth of 4.4 m, a maximum depth of 10 m and a surface area of 49.4 ha. One hundred twenty-five permanent residences line the shore of the lake. Lake level is controlled by a concrete sill dam that was constructed in 1962. The lake discharges to the Croft Drain that enters the South Branch of the Elkhart River some 8.3 km downstream.

Stable thermal stratification during summer was characteristic of Skinner Lake during the years of this study. It existed from mid-May through mid-October. Figure 2 shows a typical temperature regime for the ice-free season. The hypolimnion approached anaerobic conditions rapidly as stratification became established (Figure 3). Relative areal oxygen deficits, calculated for the interval 1 May through 15 May in 1978 and 1979 were in the range of 700-900 mg m^{-2} day^{-1}. Lakes with areal oxygen deficits greater than 550 mg m^{-2} day^{-1} were considered eutrophic or highly fertile by Hutchinson (1957). Other expressions of eutrophy for Skinner Lake included extensive growth of aquatic macrophytes such as Nymphaea odorata, Ceratophyllum demersum, and Myriophyllum spicatum, and blooms of blue-green algae (Aphanizomenon sp.). The dominant fish in Skinner Lake included small sunfish (Lepomis spp.) and crappies (Pomoxis spp.), and a large rough fish population composed of the white sucker (Catastomus commersoni) and the golden shiner (Notemigonus crysoleucas). The lake's turbidity, algal blooms, macrophytes and low oxygen conditions were blamed for a general decline in fishing quality over the last two decades (Pearson, 1978).

The area of Skinner Lake watershed was 3649 hectares, 68% of which was used for agriculture. The remaining 32% was in woodlands and wetlands. The Rimmell inlet was the most important continuously discharging surface flow to Skinner Lake. Eighty-two percent of the watershed (3091 ha) was within the Rimmell drainage system (Figure 4). Land there was put to varied crop and livestock use. Subsurface tiles were widely employed for drainage. Three smaller streams carrying tile and surface runoff entered the lake from agricultural land: the Hardendorff system drained 180 ha, the Riddle stream 107 ha, and the Weimer stream 42 ha of the watershed. The overflow from nearby Sweet Lake ran along a 0.8 km channel through a woodland to Skinner Lake. The Croft-Sweet system drained 229 ha of watershed.

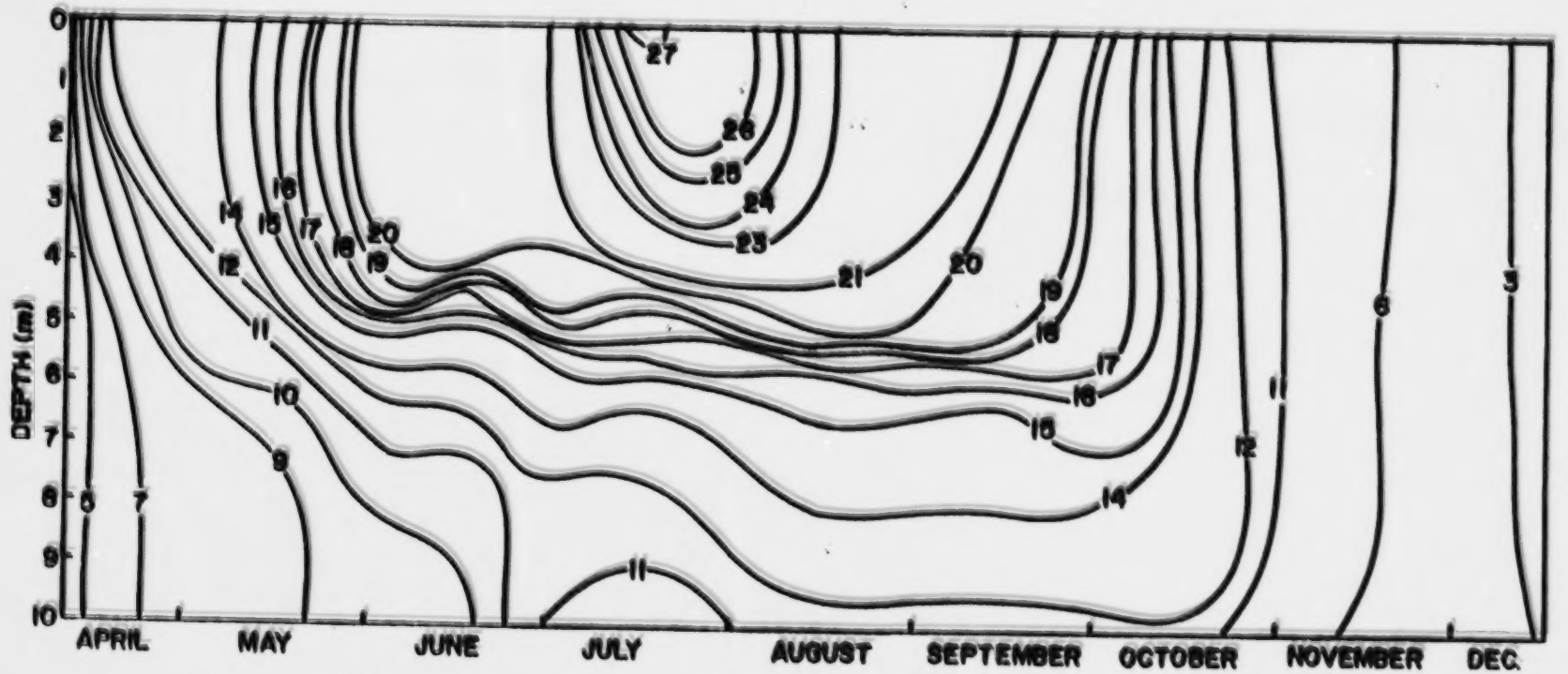

Figure 2. Temperature isopleths (°C) for Skinner Lake during the ice-free season of 1979.

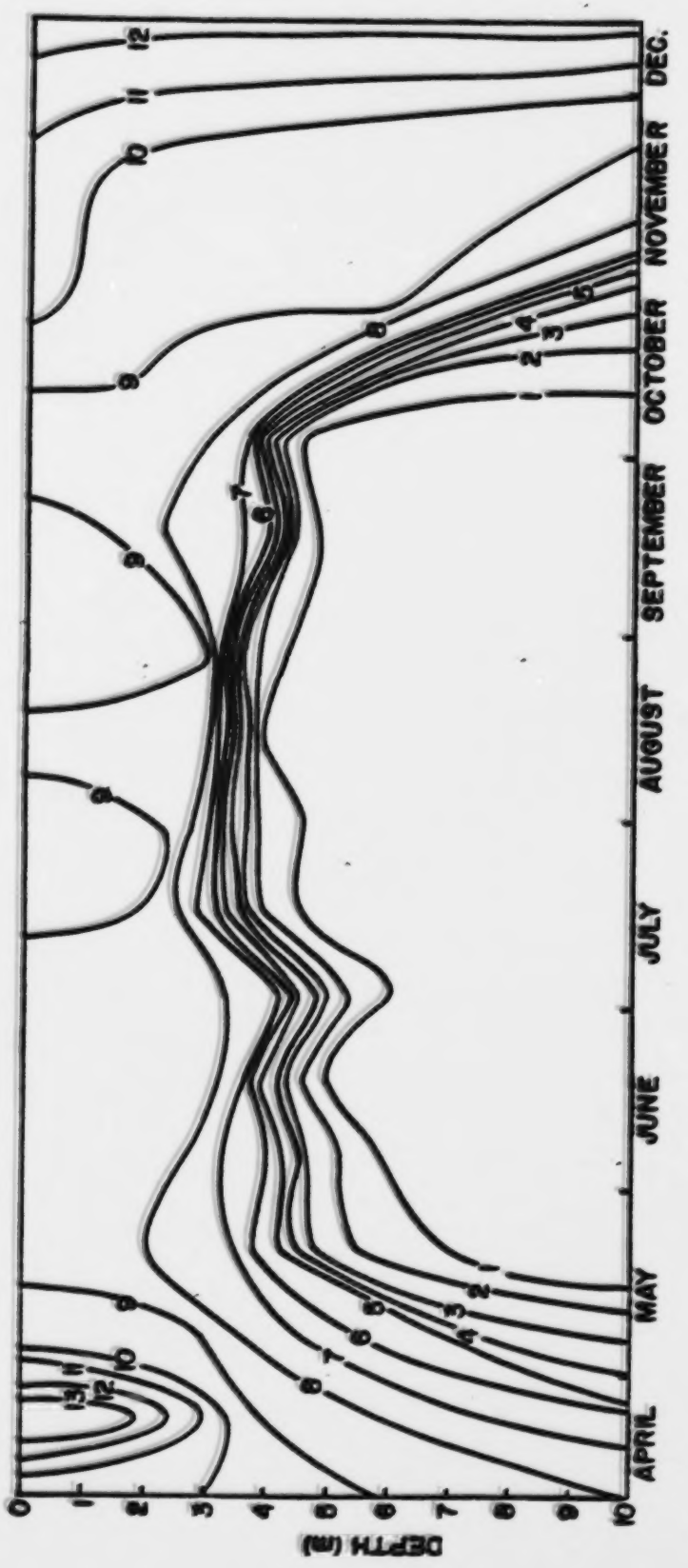

Figure 3. Dissolved oxygen isopleths (mg l^{-1}) for Skinner Lake during the ice-free season of 1979.

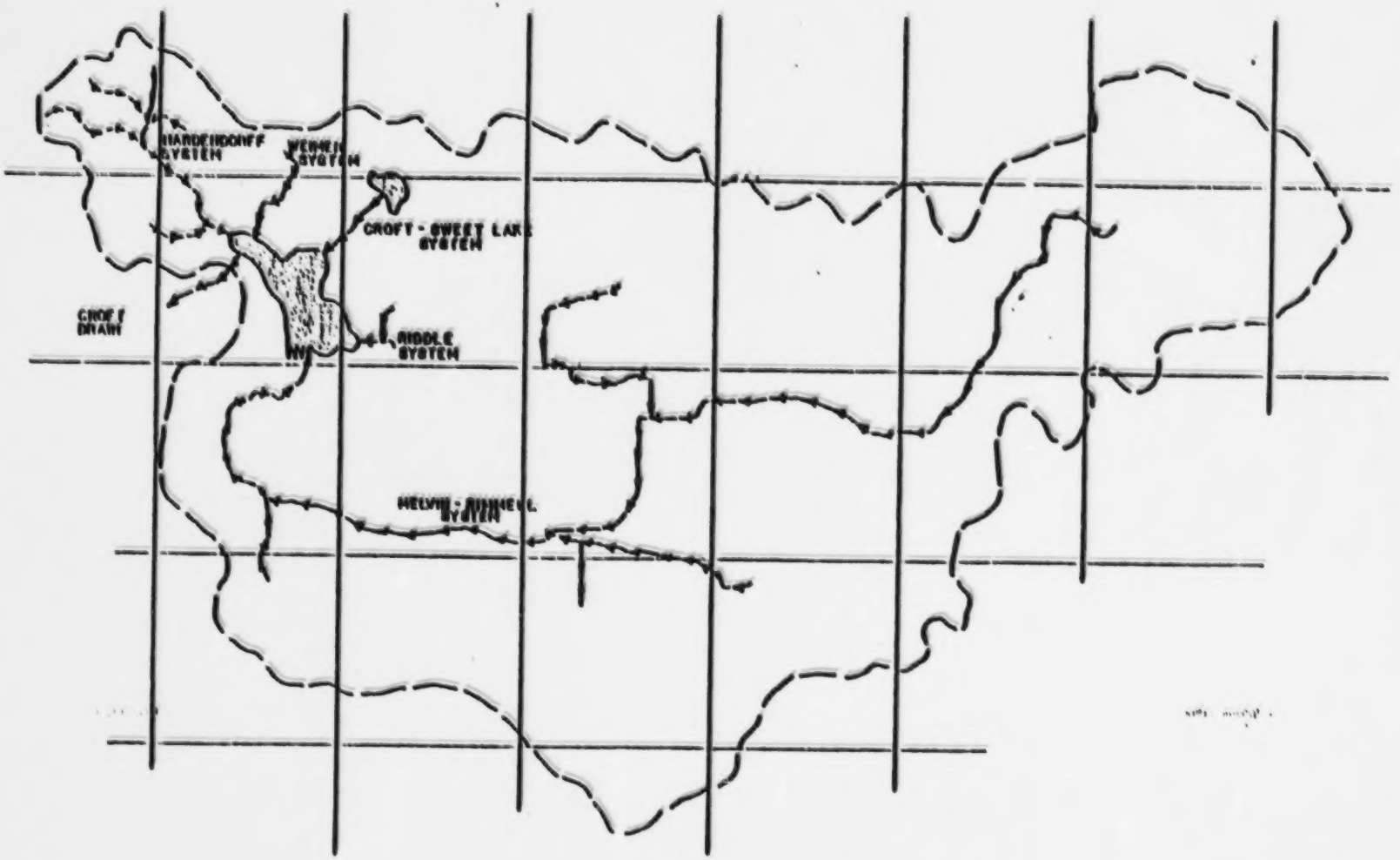

Figure 4. The Skinner Lake watershed in Noble County, Indiana. Section boundaries form the grid shown.

Methods

Studies were conducted at Skinner Lake in the interval September 1978 - September 1979, to determine $[\overline{TN}_L]$, $[\overline{TP}_L]$, $[\overline{TP}_i]$, t_w and $[\overline{chl\ a}]$ of the OECD models. Water samples were collected at two-week intervals in the ice-free period to determine $[\overline{TN}_L]$ and $[\overline{TP}_L]$. A volume-proportional scheme was used to obtain representative samples of upper pelagial and lower pelagial portions of the lake. During summer stratification, these zones were the epilimnion and hypolimnion, respectively. Volumes of water within layers of the upper and lower zones were calculated from:

$$(3) \qquad V = \frac{h}{3}\left(A_1 + A_2 + (A_1 A_2)^{\frac{1}{2}}\right)$$

where h was depth of a layer of water, A_1 was area of the upper surface of that layer, and A_2 was area of the lower surface of that layer (Wetzel, 1975). A bathymetric map of the lake was used to obtain areas. Three strata within the upper pelagial water were sampled at four stations on the lake (Figure 5), and combined to form volume-proportional composites. Similarly, water was combined from three strata in the lower pelagial zone. Composite samples were obtained in duplicate.

Samples were processed utilizing adaptations of procedures described in U.S. EPA Methods for Chemical Analysis of Water and Wastes (1971,1979a). Total phosphorus determination used persulfate oxidation followed by colorimetric determination of the antimony-phospho-molybdate complex. Total nitrogen was taken from the sum of nitrate-nitrite nitrogen and Kjeldahl nitrogen. Nitrite-nitrate-N was determined using the cadmium reduction method. In order to analyze for amounts of total Kjeldahl nitrogen, water samples were heated in the presence of concentrated sulfuric acid, K_2SO_4 and $HgSO_4$, and evaporated until SO_3 fumes were obtained and the solution became colorless. The cooled residue was diluted, and made alkaline with addition of a hydroxide-thiosulfate solution. The ammonia was determined spectrophometrically after distillation and Nesslerization. Spectrophotometric determinations were made with a Varian SuperScan 3, UV-visible spectrophorometer with a band width of 2-4 nm.

$[\overline{TN}_L]$ and $[\overline{TP}_L]$ for Skinner Lake were calculated with the following equation:

$$(4) \qquad [N_L] = \left|(V_{up} \cdot [N]_{up}) + (V_{low} \cdot [N]_{low})\right| / V_L$$

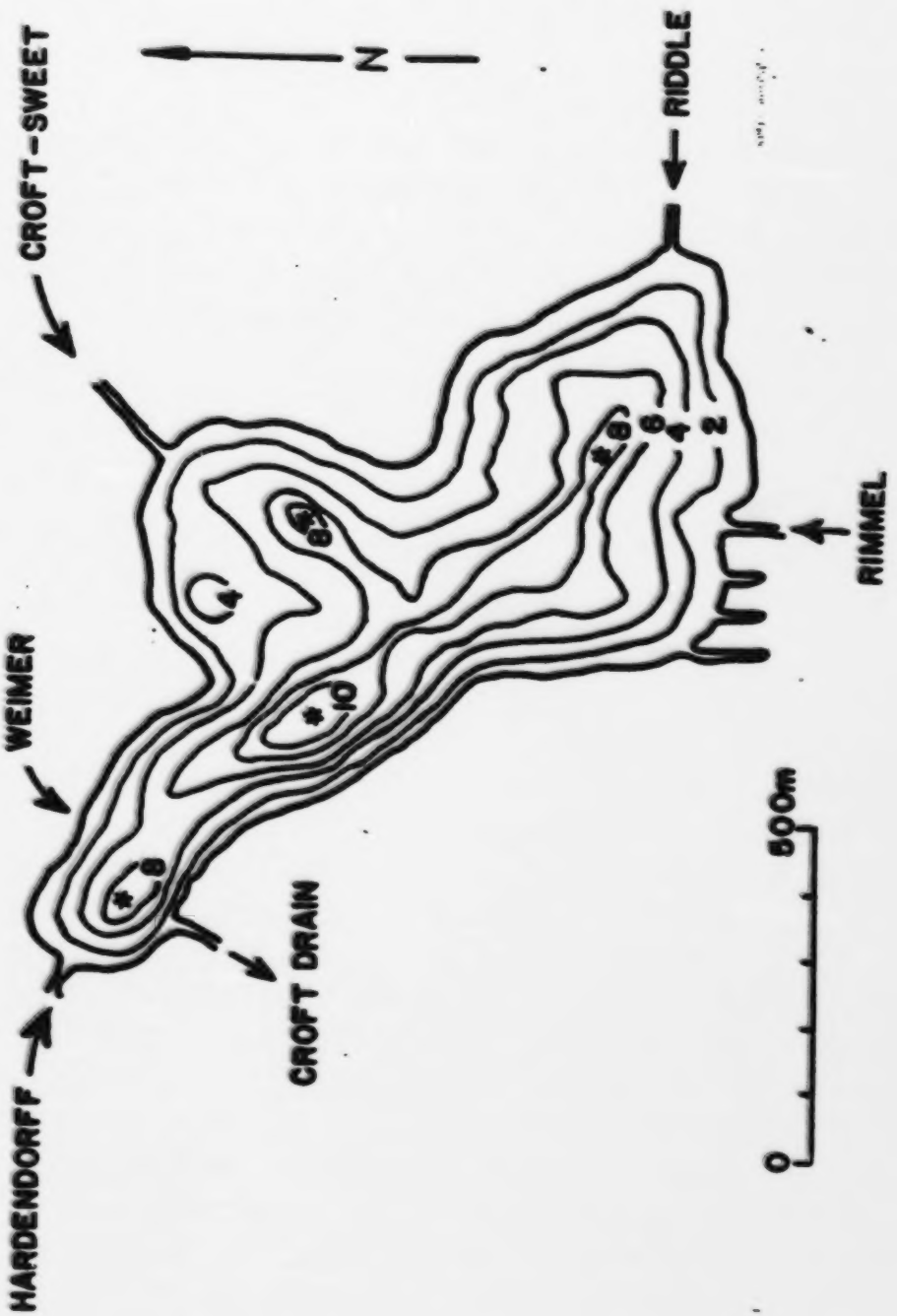

Figure 5. Bathymetry of Skinner Lake; contours are in meters. In-lake sampling stations are shown by asterisks.

where V_{up} was volume of the upper pelagial at sampling time, $[N]_{up}$ was nutrient concentration determined from upper pelagial composite sample, V_{low} was volume of the lower pelagial at sampling time, $[N]_{low}$ was nutrient concentration determined from the lower pelagial composite sample, and V_L was volume of Skinner Lake (2.157×10^6 m^3). Ratios of total nitrogen to total phosphorus ($[TN_L]/[TP_L]$) were calculated using values thus derived. Mean in-lake concentrations over the ice-free period were calculated by finding the average of the nutrient values as calculated by equation (4).

Measurements of atmospheric loading, stream loading and internal loading to Skinner Lake were made to estimate $[\overline{TP}_1]$ for the model. [TP] in atmospheric fallout was determined at intervals of two to several weeks according to the methods of Batterson and McNabb (1983). Triplicate lexan containers (23 cm deep, area = 0.26 m^2) in a stand 1 meter above the surface of the lake, were used to collect fallout. At the beginning of each period, acid cleaned containers were filled with six liters of distilled deionized water. One liter was withdrawn from each. These were combined and analyzed for beginning concentrations of TP. After exposure, interior surfaces of containers were cleaned into the water. Water from all containers was combined and mixed. Volume was measured, and 1 liter was withdrawn for analysis of end-values of [TP]. Loading was calculated from increase in mass of TP during the period of exposure.

Stream loading of total phosphorus between September 1978 and September 1979 was based on a water budget calculated for that interval. Continuous hourly stage height records were available for the two streams in the watershed with greatest discharge; the Rimmell stream and Croft Drain. Records indicated that during spring largest fluctuations of discharge occurred. On the basis of that, daily flow measurements were made during the spring of 1979 to estimate discharge for streams without recorders. During the rest of 1978-79, when fluctuations in discharge were small, flows on these streams were measured at two-week intervals. Discharge rates were determined according to the U.S. Dept. of Interior Water Measurement Manual (1967) using a pygmy Price-Gurley current meter.

Hydrographs, which represented continuous plots of discharge over time, were constructed for all streams. Hydrographs for the Rimmell stream and Croft Drain were constructed from continuous stage height records.

During summer, fall, and winter, daily records of discharge were not available for inlets other than the Rimmell stream. Consequently, an indirect method for hydrograph construction between bi-weekly discharge measurements was developed from the literature. Barnes (1940) found that after peak response to a rain event, discharge of a stream declined at a constant geometric rate characteristic of the stream in the absence of changes in its drainage basin. This rate, the recession constant (K), can be calculated as:

$$(5) \qquad K^n = \frac{q_n}{q_1}$$

where q_1 is discharge at day 1, q_n is discharge at day n, and n is the time between q_1 and q_n in days. K was calculated for the Riddle, Croft-Sweet, Weimer and Hardendorff inlets from the hydrographs of spring when daily flow measurements were available. The shape of the inlet streams' hydrographs for rain events of summer and fall was determined from these recession rates. A heated, reccrding precipitation guage installed on the watershed provided a continuous record throughout the study period. The time of rain events was given by its record. Lag-time (time from start of event to peak discharge) was determined during storms of early summer to be less than two days for all inflowing streams. The total discharge for an event was calculated based on the continuous record of discharge of the Skinner Lake outfall. Base-flow discharge from the lake and input due to rainfall on the lake were subtracted from the continuous discharge values provided during an event. Results were then plotted giving the hydrograph for total stream inputs during a precipitation event. This input was consigned to individual streams on the basis of the percentage of the total input they contributed to the lake during the most recent gaging studies. A shape, enclosing estimated discharge, was then given to the hydrograph of each stream knowing the lag-time and the slope of the recession line (K). Stream discharges for the whole year (9/6/78 - 10/3/79), and intervals of snowmelt-spring overturn-summer stratification (2/6 - 10/3/79), spring overturn-summer stratification (3/20 - 10/3/79) and summer stratification (5/21 - 10/3/79) were determined by planimetry of the stream hydrographs.

[TP] was measured in stream samples collected daily during spring of 1979. Aliquots from each stream's samples were composited over two-weeks

according to a discharge-proportional scheme (Glandon et al., 1981). Volume of aliquots was determined by considering that each sample (e.g., collected at time t_1) represented the volume of water discharged from the time halfway to the previous sample collection ($t_1 - t_0/2$) to halfway to the following sample collection ($t_2 - t_1/2$). Volume of discharge over the interval was calculated using the following equation:

$$(6) \quad v = \frac{Q_0 + 3Q}{8} (t_1 - t_0) + \frac{3Q + Q_2}{8} (t_2 - t_1)$$

where V is the volume of water discharged, and Q is the discharge rate measured at time 0, 1 and 2. Composite samples were refrigerated and acidified (2 ml conc. H_2SO_4/1), and submitted to the laboratory at two-week intervals for total phosphorus analysis. During summer, fall and winter, individual samples were collected for [TP] analysis at two-week intervals.

Mass of TP for each inlet was calculated by multiplying concentration by the total discharge of the inlet over intervals represented by water samples. Mean concentration of total phosphorus in stream flow discharged to Skinner Lake ($[\overline{TP}_i]$) was calculated by adding amounts of TP in discharge of five inflows to the lake and dividing by total volume of discharge of those streams over the interval in question.

Internal loading of TP was estimated from:

$$(7) \quad TP_{Load} = \Delta \text{ Lake Storage} - (TP_{in} - TP_{out})$$

where TP_{Load} was mass of TP internally loaded to Skinner Lake during an interval, TP_{in} was the mass of TP entering in stream flow, TP_{out} was mass of TP exiting the lake, and Δ Lake Storage was the difference in mass the lake contained between the beginning and end of an interval. TP_{Load} calculated for the ice-free season up until mid-July was zero or negative. TP_{Load} calculated for the remainder of the stratification period (7/16 - 10/3) was large and positive. Solving the equation for the interval 7/16 - 10/3/79 allowed for determination of the mass of TP in the lake due to internal loading.

OECD eutrophication models consider lake basins to be completely mixed reaction vessels. Thermal stratification in summer commonly provides

a barrier to this expectation. Year around distribution of temperature and dissolved oxygen was measured in Skinner Lake to mark the times of occurrence of overturn and depths of the epilimnion, metalimnion, and hypolimnion during summer stratification. Dissolved oxygen and temperature were measured at two-week intervals at each of four lake sampling stations during the ice-free season (Figure 4). These measurements were taken at 0.5 m depth intervals with a YSI Model 54 A oxygen meter.

Flushing coefficient (ρ) and residence time of water (t_w) were calculated for Skinner Lake. The flushing coefficient was determined as:

$$\rho = V_o/V_L \qquad (8)$$

where V_o was volume of outflow from the lake, and V_L was volume of the lake. Planimetry of the hydrograph of the Croft Drain outlet yielded lake discharge. Flushing coefficients were calculated for intervals of the year and for a whole year (9/6/78 - 9/17/79). The flushing coefficient for the epilimnion (to 4 m depth) during summer stratification was also calculated. Residence time (t_w) was the reciprocal of the flushing coefficient.

Concentrations of chlorophyll *a* in Skinner Lake were obtained to calculate $[\overline{\text{chl } a}]$ for use in the OECD expression of equation (2). Upper pelagial composite samples were collected at two-week intervals during the ice-free period of 1979. Chlorophyll *a* was determined as outlined in Strickland and Parsons (1965). Approximately 500 ml of water were filtered through Gelman Metricel Filters. Chlorophyll was extracted by grinding the filters in 90% aqueous acetone. Samples were then centrifuged. Supernatant was scanned with a Varian SuperScan 3 spectrophotometer for absorbance from 800-400 nm. The sample was acidified with HCl and rescanned from 800-400 nm. Absorbance recorded at 665 nm before and after acidifying allowed for determination of chlorophyll *a* in mg m^{-3}.

During 1982, measurements were made of $[\overline{TP_i}]$ due to streams, t_w, $[\overline{TP_L}]$ and $[\overline{\text{chl } a}]$. Data from 1978-79 showed that $[\overline{TP_i}]$ and t_w calculated over the spring overturn-summer stratification interval determined $[\overline{TP_L}]$ in the ice-free period, and that algal production in the ice-free period was related to $[\overline{TP_L}]$ by equation (2). Because of this, the period 3/24 - 8/10/82 was used for making measurements for the Skinner-specific lake

model. Water samples from each inlet were collected daily during 3/24 - 6/30/82 using the same methods of compositing and TP analysis as in 1978-79. From 6/31 - 8/10/82, daily sampling was deleted and water from each inlet was collected and analyzed at two-week intervals. $[TP_i]$ from streams was determined in 1982 from measured [TP] and a water budget from the interval 3/24 - 8/10/82. The water budget was obtained using the techniques of 1978-79. Measurements of discharge from the lake were used to calculate residence time of water in Skinner Lake (t_w).

Samples from the lake's outflow were taken from 3/24 - 9/13/82 to determine $[\overline{TP}_L]$ and $[\overline{\text{chl } a}]$. Mean [TP] of the epilimnion during summer of 1979 ($\bar{x}$ = 44 mg m^{-3}, s = 16) was essentially the same as that of Skinner Lake's outflow ($\bar{x}$ = 45 mg m^{-3}, s = 27). This followed the prediction of Chapra (1975) that the concentration in outflowing water will be equivalent to that in surface water at mid-lake in small well-mixed systems.

Results

Concentrations of nitrogen and phosphorus in Skinner Lake in 1979 and reported in Table 1. Total nitrogen concentrations diminished from high values in the spring to low values in later summer and fall. The pattern of decrease in [TN] was much the same for concentrations calculated for the whole lake volume and for the epilimnion only. The range observed of [TN] was 5.88 - 1.19 mg m^{-1}. Regarding [TP], a range of 0.021 - 0.199 mg l^{-1} was observed. High whole-lake [TP] in the interval July 30 - October 3 resulted primarily from high TP concentrations in the hypolimnion. They ranged from 0.154 - 0.221 mg l^{-1} during that time. Phosphorus was apparently released across the anaerobic sediment surface that existed in the hypolimnion (Figure 6). It can be noted from Table 1 that concentrations of TP in the epilimnion from July 30 to October 3 were approximately 50% of whole-lake concentrations during that time. Whole-lake [TP] changed abruptly in October with initiation of fall overturn; concentration fell from 0.120 to 0.043 mg l^{-1}. Coincidence of overturn and decrease in [TP] suggest that phosphorus, particularly that in the hypolimnion, fell out to the sediments (Figure 6). Solving equation (7) for phosphorus mass balance in the lake basin for the period when fall overturn was initiated (October 3 - October 24) supported this suggestion.

Estimates of internal phosphorus loading were calculated for intervals of the ice-free period of 1979 (equation (7)). These were negative for intervals of measurement after ice-out until mid-July. By these calculations, a net loss of phosphorus occurred during that time. For the interval July 16 - October 3, internal loading to the water column was calculated to be 120 kg TP. From the perspective of the OECD models, this phosphorus influenced the magnitude of $[\overline{TP}_1]$ in the Skinner Lake system.

Total nitrogen:total phosphorus for the epilimnion of Skinner Lake are given in Table 1. They were found to range from 19 to 220. The work of Sakamoto (1966), Chiaudani and Vighi (1974), Allen and Kenny (1978), Smith and Shapiro (1980) and Smith (1982) predicts that at [TN]/[TP] greater than 19, nitrogen limitation did not occur in Skinner Lake,and that algal yield in the epilimnion was likely phosphorus dependent.

Atmospheric bulk loading measurements of TP on Skinner Lake for the study interval of 1978-1979 are given in Table 2. Atmospheric loading amounted to 0.04 g TP m^{-2} per year. While this measurement fell within

Table 1. Concentrations of nitrogen and phosphorus (mg l^{-1}) in Skinner Lake during the ice-free period in 1979. [TN]/[TP] are given for whole lake during spring and fall overturns and epilimnion during summer stratification.

Date	Whole Lake [TN]	Whole Lake [TP]	Hypolimnion[a] [TN]	Hypolimnion[a] [TP]	Epilimnion[a] [TN]	Epilimnion[a] [TP]	[TN]/[TP]
March 19	5.85	0.199					29
April 1	5.88	0.177					50
April 15	5.42	0.093					58
April 23	5.61	0.068					83
May 7	4.50	0.047					96
May 21	4.54	0.055	4.44	0.075	4.65	0.031	150
June 5	3.57	0.036	2.52	0.050	4.61	0.021	220
June 18	3.42	0.037	3.82	0.045	2.92	0.027	108
July 2	2.95	0.067	2.97	0.078	2.94	0.060	49
July 16	2.75	0.042	2.58	0.062	2.90	0.024	121
July 30	3.28	0.081	2.93	0.154	3.50	0.034	103
August 13	1.94	0.137	2.78	0.221	1.19	0.062	19
August 21	1.91	0.106	2.74	0.198	1.48	0.059	25
September 17	2.69	0.121	3.81	0.203	1.69	0.048	35
October 3	1.82	0.120	2.50	0.196	1.20	0.052	23
October 24	1.28	0.043					30
November 14	1.38	0.036					32
December 12	3.07	0.044					70
Means	3.44	0.081	3.11	0.128	2.71	0.042	72

a. Lake stratified May 21 through October 3.

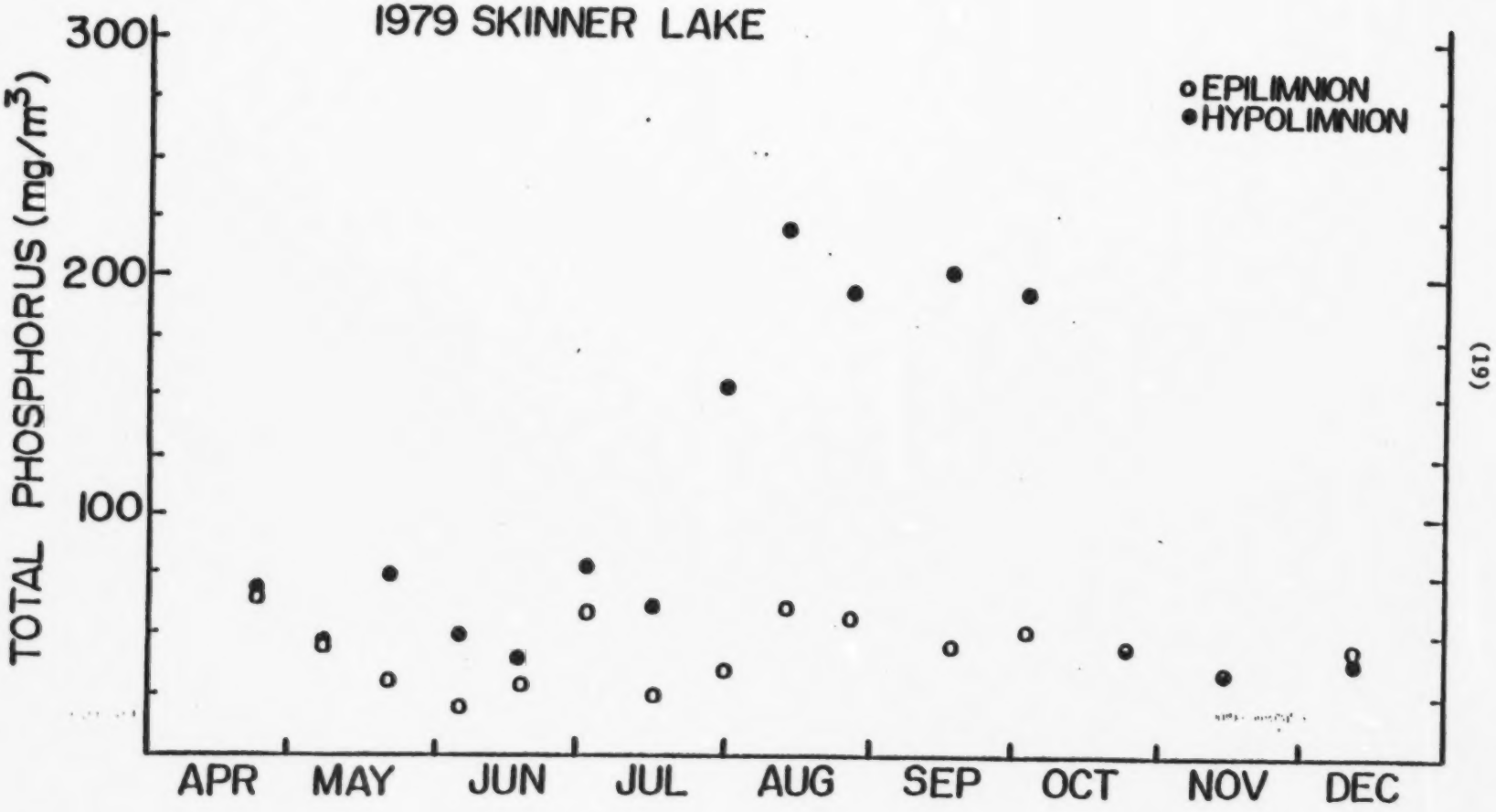

Figure 6. Total phosphorus concentration (mg l^{-1}) in Skinner Lake during the ice-free season of 1979.

Table 2. Atmospheric bulk loading of total phosphorus on Skinner Lake during the interval 9/6/78 - 9/17/79.

Period	Rate of Fallout (mg m^{-2} day^{-1})	Input to Lake (kg day^{-1})
9/6 - 9/25/78	0.099	0.049
9/25 - 10/9/78	0.045	0.022
10/9 - 10/23/78	0.117	0.058
10/23 - 11/6/78	0.066	0.033
11/6 - 11/27/78	0.050	0.024
11/27 - 12/14/78	0.092	0.045
12/14 - 1/16/79	0.041	0.020
1/16 - 2/6/79	0.023	0.011
2/6 - 4/2/79	0.074[1]	0.036[1]
4/2 - 4/23/79	0.125	0.061
4/23 - 5/7/79	0.107	0.052
5/7 - 5/21/79	0.378	0.185
5/21 - 6/18/79	0.145	0.071
6/18 - 7/2/79	0.108	0.053
7/2 - 7/16/79	0.059	0.029
7/16 - 7/30/79	0.126	0.062
7/30 - 8/13/79	0.607	0.298
8/13 - 8/27/79	0.222	0.109
8/27 - 9/17/79	0.163	0.080

1. Sampling disrupted: values are the average between the previous and following intervals.

the range predicted for the region by Chapin and Uttormark (1973), it constituted only 1.4% of the annual stream loading. Hence, the influence of atmospheric loading on model $[\overline{TP}_i]$ was small at Skinner Lake.

Stream hydrographs were developed for the annual period of study in 1978-79. Seasonal patterns of discharge observed at Skinner Lake are shown for the Rimmell stream in Figure 7. Other hydrographs made in this study are in Appendix I. These hydrographs were divisible into periods of fall and winter runoff, runoff due to melt of snowpack, discharge during spring overturn, and discharge during summer stratification. Discharges of streams during these periods are reported in Appendix II (Table A-1). Total discharge associated with melt of the snowpack amounted to 53% of the annual stream discharge to the lake in 1978-79. Stream discharge from rains during spring overutrn accounted for 35% of annual discharge. In 1979, hydrographs for inflowing streams remained near base flow during summer stratification. Base flows of summer, fall and winter provided 12% of annual runoff to the lake.

Flushing coefficients (ρ) for Skinner Lake for 1978-1979 are given in Table 3. Coefficients are broken down in Table 3 by periods of the year. High observed coefficients during snow melt and spring rains and low coefficients for other times of the year are likely typical of small-volume temperate zone lakes with relatively large watersheds. It can be noted that runoff from snow-melt tended to displace the volume of water in the lake basin. This occurred during the period of ice-off from the lake. Subsequent runoff from rains freshened the lake during spring overturn. Coincident with relatively low stream discharges to the lake in summer, the flushing coefficient during stratification was small.

Concentrations of TP measured in inlet streams during 1978-79 are reported in Appendix II (Table A-2).

Spring runoff of phosphorus dominated stream $[\overline{TP}_i]$ during the 1978-79 annual interval. For example, Figure 8 for the Rimmell stream can be used to demonstrate that approximately 90% of the annual loading of TP from that watershed was delivered to Skinner Lake during snowmelt and spring overturn periods (February - May). For the five inlets to the lake taken collectively, 93% of annual TP loading occurred during this interval. For the year, calculated stream $[\overline{TP}_i]$ was 231 mg m^{-3}.

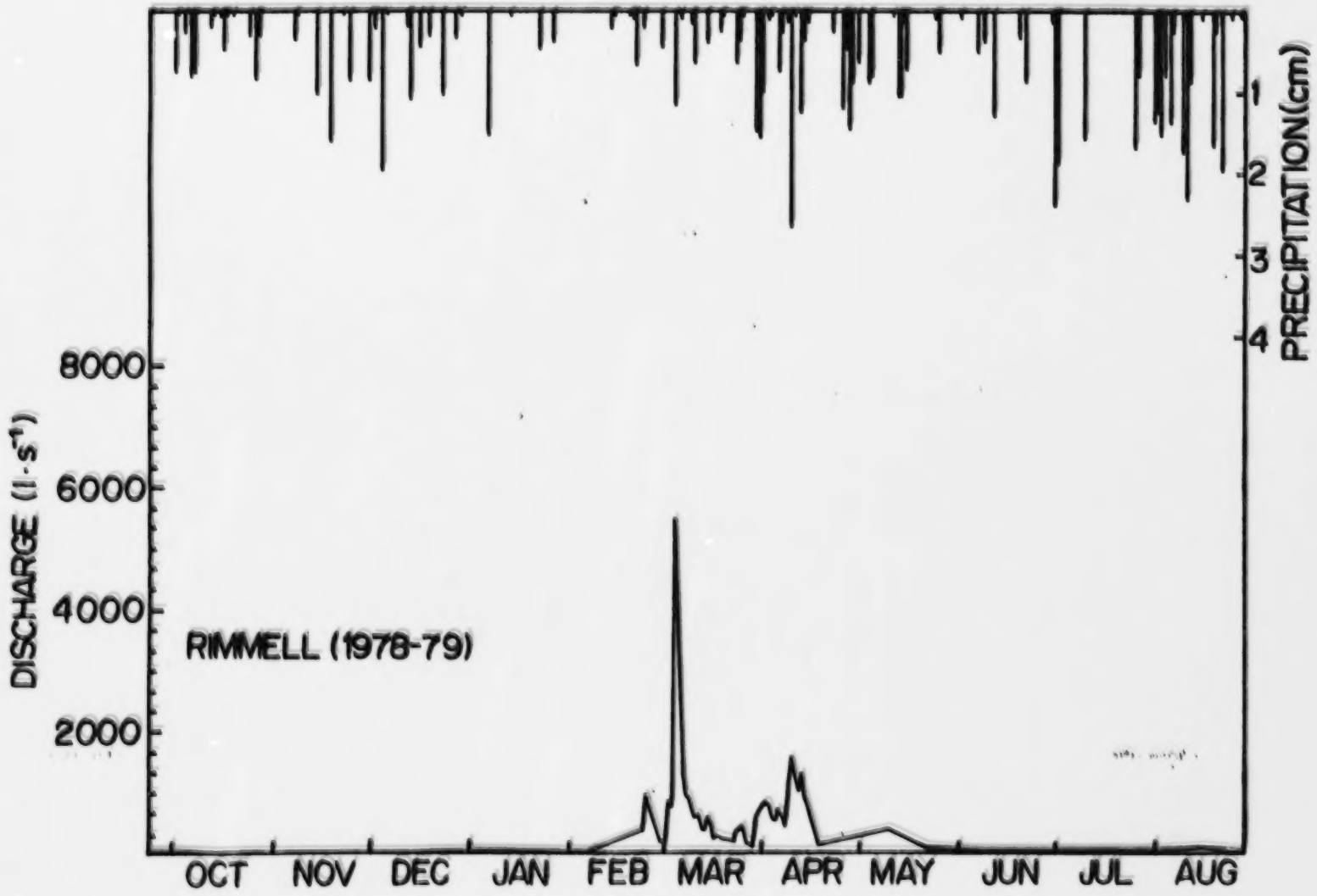

Figure 7. Stream flow hydrograph for the Rimmell inlet during 1978-1979.

Table 3. Flushing coefficients (ρ) of Skinner Lake during periods of 1978–79.

Period	(ρ)
Fall Overturn and Winter 9/6/78 - 2/6/79	0.02
Snow Melt 2/6 - 3/20/79	1.30
Spring Overturn 3/20 - 5/22/79	1.06
Summer Stratification 5/22 - 9/6/79	0.17
Whole Year 9/6/78 - 9/6/79	2.55

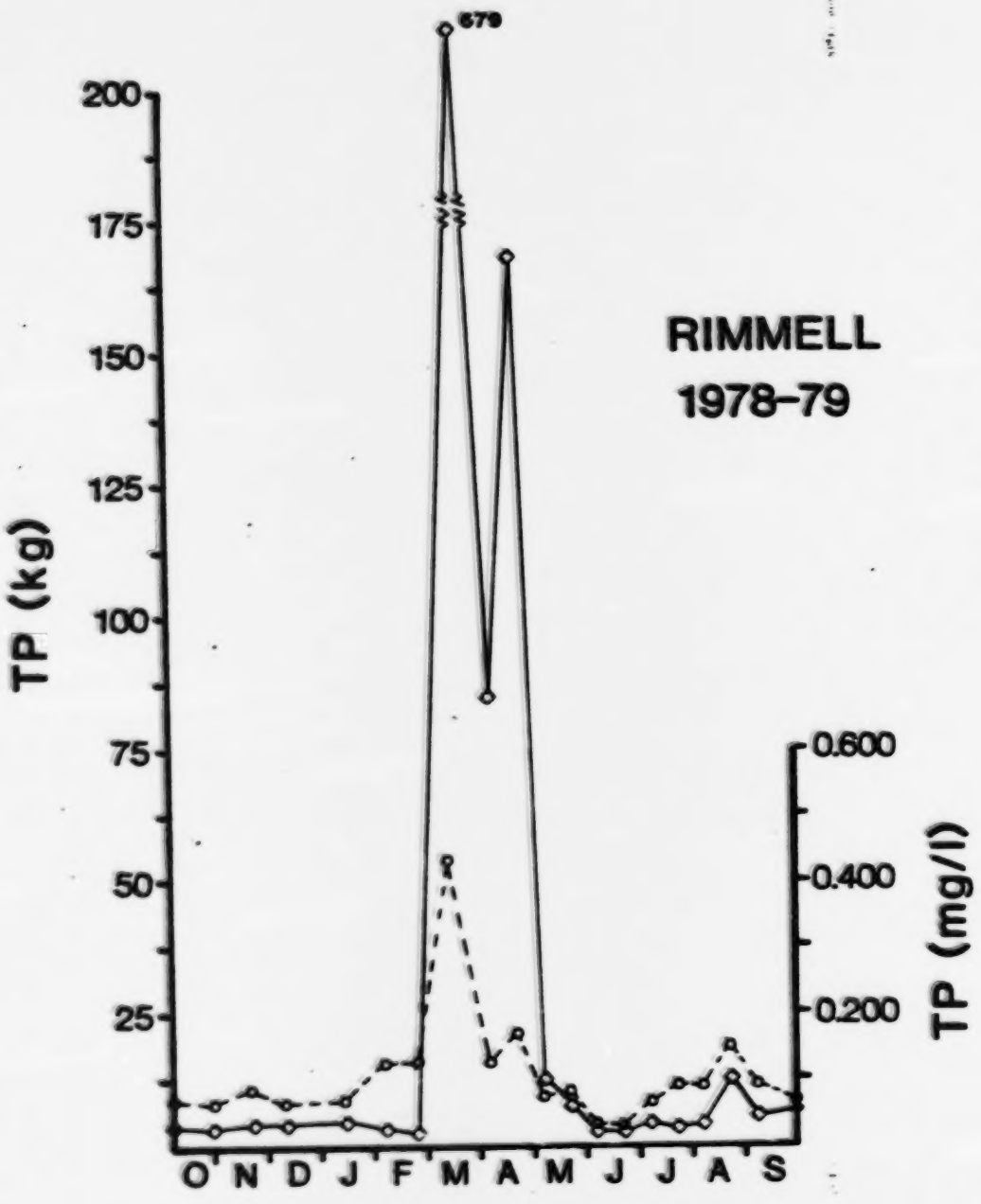

Figure 8. Concentration (mg l^{-1}) and mass (kg) of total phosphorus (TP) delivered to Skinner Lake by the Rimmell inlet during 1978-79.

Data given above for 1978-79 were used to develop a model for the Skinner Lake system. The model stated that $[\overline{TP_L}]$ and $[\overline{\text{chl } a}]$ in Skinner Lake in the ice-free period were predictable from t_w and $[\overline{TP_i}]$ from streams derived for the period of spring overturn and summer stratification, rather than for the entire year, or a period that included runoff during melt of the snowpack.

Measurements to test the predictability of the Skinner-specific model and to describe post land-treatment changes in the system, were made in 1982. Discharge and [TP] in streams measured in 1982 are reported in Apendix II (Tables A-4 and A-5). During the interval of measurement (4/20 - 8/10/82), t_w was 0.65, $[\overline{TP_i}]$ from streams was 99.6 mg m^{-3}, and $[\overline{TP_L}]$ was 63 mg m^{-3}. By the relationship of equation (2), $[\overline{\text{chl } a}]$ in the ice-free period was expected to be less in 1982 than in 1979. Chlorophyll data for these years are given in Table 4. A depression in $[\overline{\text{chl } a}]$ from 15.15 mg m^{-3} to 9.58 mg m^{-3} occurred between years.

Table 4. Concentration of chlorophyll a (mg m^{-3}) in Skinner Lake during summer of 1979 and 1982.

1979		1982	
Date	[chl a]	Date	[chl a]
4/23/79	24.80		
5/7/79	11.59	5/4/82	7.48
5/21/79	6.27	5/18/82	4.01
6/18/79	12.05	6/2/82	8.01
7/2/79	18.96	6/18/82	9.35
7/16/79	9.36	6/28/82	5.34
7/30/79	13.26	7/14/82	16.02
8/13/79	12.21	7/28/82	16.02
8/27/79	20.42	8/10/82	9.35
9/17/79	16.70	9/13/82	10.68
10/3/79	21.00		
	$\bar{x}$ = 15.15		$\bar{x}$ = 9.58

Discussion

The Vollenweider and Kerekes (1980) model was applied to the Skinner Lake system to quantify the relationship of $[\overline{TP}_i]$ to $[\overline{TP}_L]$ and $[\overline{\text{chl } a}]$. From 1978-79 data of this study, the model was specifically modified to fit the conditions of Skinner Lake. To make modifications, the following were considered: major sources of $[TP_i]$ to Skinner Lake, seasonal differences in $[TP_i]$ and t_w, and differences in epilimnetic and hypolimnetic $[TP_L]$ and their relation to $[\overline{\text{chl } a}]$.

Vollenweider and Kerekes (1980) did not specify sources of $[TP_i]$ measured to derive the empirical basis for their model. Atmospheric loading, septic tank loading, internal loading, and stream loading can be important sources of $[TP_i]$ for lakes. The influence of atmospheric TP loading on $[\overline{TP}_i]$ of Skinner Lake was found in this study to be negligible. Septic tank loading was estimated using the constant, 0.08 kg TP caput^{-1} yr^{-1}, reported by Walker (1979). There were 125 cottages and approximately 375 people served by septic tanks around Skinner Lake. By Walker's constant, these contributed 30 kg TP yr^{-1}. This septic tank loading comprised 2% of the 1978-79 annual total TP load. Internal phosphorus loading during summer has been found to be an important contributor to $[TP_i]$ in some eutrophic lakes (Nurnberg, 1982). In Skinner Lake during summer of 1979, the estimated 120 kg of internal TP loading comprised 8% of the 1978-79 total TP load. Of the potential sources, stream loading was the major component of $[\overline{TP}_i]$ at Skinner Lake, comprising 90% of the annual total TP input.

There is inference in their work that Vollenweider and Kerekes calculated $[\overline{TP}_i]$ and $[\overline{TP}_L]$ by averaging data over an annual period. However, in the Skinner Lake system there was great seasonal variation in both $[\overline{TP}_i]$ and t_w over a year. These variations effected the model predictions of $[\overline{TP}_L]$ in ways that are shown in Table 5. A comparison of rows I and II in Table 5 shows that base-flow conditions of streams in fall and early winter (9/6/78 - 2/5/79) had little effect on determining the magnitude of annual $[\overline{TP}_i]$ and t_w. For the whole year and for the interval including snowmelt, spring overturn, and summer stratification, the Vollenweider and Kerekes model greatly overestimated $[\overline{TP}_L]$. A comparison of rows II and III in Table 5 shows the importance of the snowmelt period for determining the magnitude of annual $[\overline{TP}_i]$ and t_w. During that interval

Table 5. Fit of Skinner Lake data of 1978-79 to Vollenweider and Kerekes (1980) estimates of in-lake $[\overline{TP}]$ calculated from:

$$[\overline{TP}_L] = \frac{[\overline{TP}_i]}{1 + t_w^{\frac{1}{2}}}$$

where $[\overline{TP}_i]$ is from stream discharges except for III B.

	Period		$[\overline{TP}_i]$ (mg m^{-3})	t_w	Predicted $[\overline{TP}_L]$ (mg m^{-3})	Observed $[\overline{TP}_L]$ (mg m^{-3})
I.	Whole Year 9/6/78-10/3/79		231	0.39	142	85
II.	Snowmelt-spring overturn-summer stratification 2/6-10/3/79		234	0.41	143	98
III.	Spring overturn-summer stratification 3/20-10/3/79	(A)	127	0.63	71	88
		(B)	163[1]	0.63	91	88
		(C)	127	0.63	71	63[2]
IV.	Summer stratification[3] 5/22-10/3/79		89	3.38	31	80

1. Internal loading was added to stream loading to calculate $[\overline{TP}_i]$.
2. Observed $[\overline{TP}_L]$ was calculated by averaging whole lake $[\overline{TP}_L]$ for the period of spring-overturn that constitutes one flushing time prior to stratification and epilimnetic $[\overline{TP}_L]$ during summer stratification.
3. Whole-lake volumes and concentrations were used to calculate $[\overline{TP}_L]$.

(2/6 - 3/20/79) both [TP] and discharge in inlet streams were high (Figure 8). In contrast, the large mass of TP delivered during snowmelt did not greatly influence observed $[\overline{TP}_L]$ as given in rows I, II, and IIIA. $[\overline{TP}_i]$ and t_w taken for the period of spring overturn and summer stratification provided a better prediction of $[\overline{TP}_L]$ in the Vollenweider and Kerekes model than annual estimates of these variables, or estimates using other periods of the year. This is shown in section III of Table 5. $[\overline{TP}_L]$ predicted form $[\overline{TP}_i]$ and t_w during summer stratification grossly underestimated observed $[\overline{TP}_L]$ (Table 5, row IV).

The Vollenweider and Kerekes (1980) model assumes that lakes are mixed reactors in which [TP] is homogeneous. Skinner Lake was an exception to this in that hypolimnetic [TP] was more than twice that of epilimnetic [TP] during the last one-half of the summer stratification period (Figure 6). In this study, whole-lake $[\overline{TP}_L]$ was calculated for the spring overturn-summer stratification period using TP mass and volume of water in both the epilimnion and hypolimnion. This yielded a $[\overline{TP}_L]$ for the interval of 88 mg m^{-3}. Row IIIA of Table 5 shows that whole-lake $[\overline{TP}_L]$ was underestimated using the Vollenweider and Kerekes model with measured values of $[\overline{TP}_i]$ and t_w. A closer prediction of whole-lake $[\overline{TP}_L]$ was achieved by including internal TP load with stream TP load in the $[\overline{TP}_i]$ term (Table 5, Row IIB). Specifically, this was achieved by adding 120 kg of internal laod to TP mass from stream load and dividing by stream discharge. The better fit obtained suggests that $[\overline{TP}_i]$ should include both stream and internal loading when predicting whole-lake $[\overline{TP}_L]$ for Skinner Lake during the spring-summer interval.

A major goal of this study was to predict $[\overline{chl\ a}]$ in the ice-free period from $[\overline{TP}_i]$ and $[\overline{TP}_L]$. Use of whole-lake $[\overline{TP}_L]$ measured in the spring-summer interval in equation (2) of the Vollenweider and Kerekes model predicted $[\overline{chl\ a}]$ in Skinner Lake at 22.65 mg m^{-3}. Observed $[\overline{chl\ a}]$ during 1979 was a relatively poor fit at 15.15 mg m^{-3}. It is likely that algae grow in response to [TP] of the epilimnion (Smith and Shapiro, 1981). On this basis, an alternate method of calculating $[\overline{TP}_L]$ was considered. It averaged whole-lake [TP] during spring overturn and epilimnetic [TP] during summer stratification (Table 1). From measurements of this study, the resulting $[\overline{TP}_L]$, designated $[\overline{TP}_{epi}]_{ss}$, was 63 mg m^{-3}. Using this value in equation (2), predicted

observed $[TP_{epi}]_{ss}$ relatively well. From these considerations, $[\overline{TP}_i]$ of Vollenweider and Kerekes was treated as $[\overline{TP}_{stream}]_{ss}$ and $[\overline{TP}_L]$ as $[\overline{TP}_{epi}]_{ss}$ for purposes of modeling the effect of incoming phosphorus and algal yield in Skinner Lake. Further, a spring overturn period was used in the study of 1979 to coincide with the interval of time prior to stratification during which the flushing coefficient of the lake approximated 1.0 (Table 3). The spring period as applied to variables (e.g. $[\overline{TP}_{stream}]_{ss}$) in the Skinner-specific model was defined by this. Records of the U.S. Weather Bureau for 1979 showed it was a relatively dry year at Skinner Lake. Basing a model on a spring period where $\rho = 1$ appeared appropriate for this system.

The Skinner-specific model based on above considerations took the form:

$$(9) \quad a. \quad [\overline{TP}_{epi}]_{ss} = \frac{[\overline{TP}_{stream}]_{ss}}{1 + t_{w_{ss}}^{\frac{1}{2}}}$$

$$b. \quad \log [\overline{chl\ a}]_{ss} = 0.99 \log [\overline{TP}_{epi}]_{ss} - 0.60$$

where $[\overline{TP}_{epi}]_{ss}$ was mean TP concentration of the epilimnion over the spring-summer stratification (ss) interval, $[\overline{TP}_{stream}]_{ss}$ was mean TP concentration delivered to the lake from the inlet streams over the ss interval, $t_{w_{ss}}$ was residence time of water in the lake over the ss interval, and $[\overline{chl\ a}]_{ss}$ was mean chlorophyll *a* concentration in the epilimnion over the ss interval. The constant in the Vollenweider and Kerekes relationship for $[\overline{chl\ a}]$ and $[\overline{TP}_L]$ given in equation (2) was changed (0.57 to 0.60) to fit the observed conditions of Skinner Lake during 1978-79.

Following land treatment during 1979-1981, the Skinner-specific model proved to be an accurate predictor of $[\overline{TP}_{epi}]_{ss}$ and $[\overline{chl\ a}]_{ss}$. In 1982, $[\overline{TP}_{stream}]_{ss}$ was 100 mg m^{-3} as compared to 127 mg m^{-3} in 1979. Concomitant decreases in $[\overline{TP}_{epi}]_{ss}$ and $[\overline{chl\ a}]_{ss}$ were expected as predicted by equations (9a) and (9b). Predicted $[\overline{TP}_{epi}]_{ss}$ for 1982 was 55 mg m^{-3}; observed was 54 mg m^{-3}. Predicted $[\overline{chl\ a}]$ was 13 mg m^{-3}; observed was 10 mg m^{-3}.

Figure 9 is a graphical representation of the Skinner-specific model modified from Figure 8 of Vollenweider and Kerekes (1980). This figure illustrates that given $[\overline{TP}_{stream}]_{ss}$ and t_w, $[TP_{epi}]_{ss}$ is

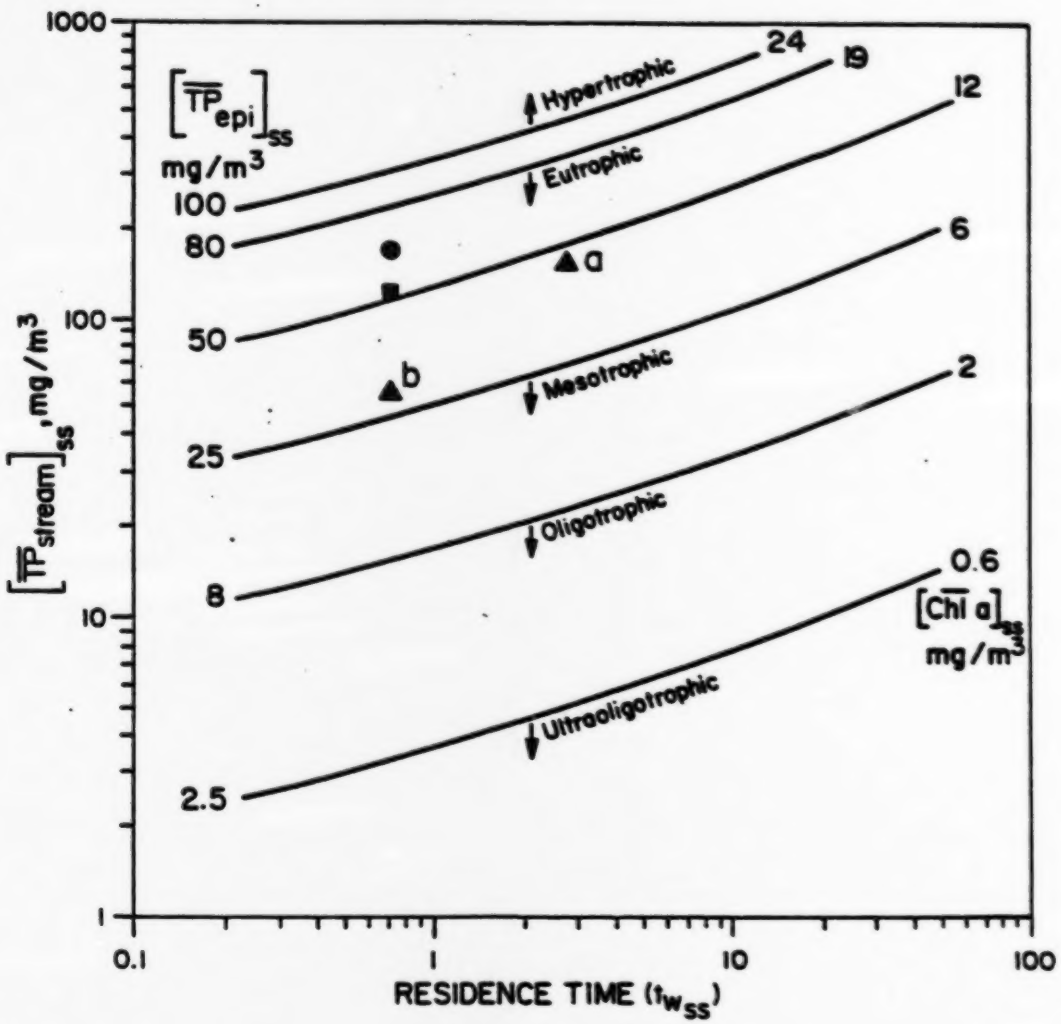

Figure 9. Diagranatic representation of the Skinner-specific model (modified from Vollenweider and Kerekes, 1980). ● represents plot of Skinner Lake coordinates of 1979; ■ represents plot of Skinner Lake coordinates of 1982; $▲^{a}$ probable case for Skinner Lake with diversion of Rimmell stream around lake to outlet stream; $▲^{b}$ probable case for Skinner Lake if settling basin on Rimmell stream removed 100% TP in stream discharge.

predicted. Curves across the figure give expected $[\overline{\text{chl a}}]_{ss}$. Included on Figure 9 are plots of Skinner Lake data for 1979 and 1982. The figure also shows boundaries of trophic categories (ultraoligotrophic to hypertrophic) as presented by Vollenweider and Kerekes (1980). These represent the synthesis of opinions of OECD investigators as to the trophic classification of their study lakes, based on $[\overline{TP}_L]$ and $[\overline{\text{chl a}}]$. In this classification, Skinner Lake falls within eutrophic status.

In the used of models such as have been discussed, a range of uncertainty exists within which predicted values vary from observed. This uncertainty may reduce the power of conclusions which are based on lake modelling schemes (Reckhow, 1979). In order to calculate confidence limits of model predictions, it is necessary to determine standard error from the variation among lakes used to construct the particular model. Two current lake models (Reckhow, 1977 and Walker, 1979) consider the statistical uncertainty of predictions of lake phosphorus concentrations, and both give a method by which confidence limits can be calculated. Confidence intervals for predictions made by these models can be estimated from:

$$(10) \qquad S_t^2 = \left| P_e - 10^{\log P_e \pm s_m} \right|^2$$

where S_t is the total prediction error in mg l^{-1}, s_m is the standard error of the estimate for the model, and P_e is the predicted lake concentration (Reckhow, 1981). Table 6 compared predictions made by the Skinner-specific, Reckhow (1977) and Walker (1979) models for phosphorus in Skinner Lake in 1979. For the purpose of this comparison, $[\overline{TP}_i]$ was taken as $[\overline{TP}_{stream}]_{ss}$, and $[\overline{TP}_L]$ as $[\overline{TP}_{epi}]_{ss}$ in the Reckhow and Walker models. Table 6 also presents the predicted confidence intervals of these models. In both cases, the confidence intervals are wide, and it is difficult to apply them to a particular lake for management decision purposes. It should be noted that error terms were estimated from least squares analysis on a data set from many lakes. Thus, much of the error results from variability between these lakes (Reckhow, 1977). When a model is applied to a particular lake, the model error term should only include that lake's variability. For example, if the Skinner-specific model was applied to Skinner Lake for several years, a series of predicted and observed values would allow determination of the certainty expected for

Table 6. Comparison of the predictions of $[\overline{TP}_L]$ from $[\overline{TP}_i]$[1] and t_w using three models. Observed lake concentration[2] = 63 mg m^{-3}.

Model and S_m[3]	Model Equation[4]	Predicted $[\overline{TP}_L]$ (mg m^{-3})	Confidence Limit[5] (mg m^{-3})
Skinner-specific	$[\overline{TP}_L] = \frac{[\overline{TP}_i]}{1 + t_w^{\frac{1}{2}}}$	71	-----
Reckhow (1977) S_m = .105	$[\overline{TP}_L] = \frac{[\overline{TP}_i]}{1.13 + .17\ t_w}$	103	$(81<[\overline{TP}_L]<131)$
Walker (1977) S_m = .171	$[\overline{TP}_L] = \frac{[\overline{TP}_i]}{1 + .824\ t_w^{.454}}$	76	$(51<[\overline{TP}_L]<113)$

1. $[\overline{TP}_i]$ is $[\overline{TP}_{stream}]_{ss}$ from the Skinner-specific model, 1979 (127 mg m^{-3}).
2. Observed $[\overline{TP}_{epi}]_{ss}$ for Skinner Lake during 1979.
3. S_m = standard error of the estimate for the model.
4. Where $[\overline{TP}_L]$ = average lake phosphorus concentration, $[\overline{TP}_i]$ = average streamflow phosphorus concentration and t_w = residence time of water in the lake (yr).
5. ± one standard error; i.e. 68% of time the true value will fall within range.

the model on Skinner Lake. This would provide more appropriate confidence estimates for management decisions at Skinner Lake.

When a model can be calibrated to fit a specific lake's characteristics using data from several years, it then becomes a powerful management tool. Use of this model could predict the effectiveness of potential management schemes, and costly projects which predict only little improvement in lake quality could be avoided. One treatment considered by planners of the Skinner Lake reclamation project was diversion of the Rimmell stream directly to the lake's outlet. Contours of the existing landscape favored such an approach, but compensation for disrupting intervening land use would have been costly. The Skinner-specific model can predict the effect of this project if, for example, it had been implemented in 1979. Figure 9 shows that diversion of the Rimmell would not have lowered $[\overline{TP}_{stream}]_{ss}$ appreciably. Other inlets were important in determining total $[\overline{TP}_{stream}]_{ss}$. Because the Rimmell provided a large percentage of inflow water to Skinner Lake, diverting the stream would have increased $t_{w_{ss}}$ from 0.63 to 2.35. The net effect of diverting the Rimmell would have been to reduce the $[\overline{TP}_{epi}]_{ss}$ from 63 mg m^{-3} to 45 mg m^{-3} and $[\overline{chl\ a}]_{ss}$ from 15 mg m^{-3} to 11 mg m^{-3}.

As a second example, a settling basin was constructed on the Rimmell inlet just above Skinner Lake during 1980-81 (Figure 1). This basin was intended to slow Rimmell water velocity and promote settling and removal of suspended particulate material. However, the basin was too small and its intended effect was much less than optimum (McNabb et al., 1982). On the basis of 1979 data, if the basin removed 100% of particulate phosphorus from the water, $[\overline{TP}_{stream}]_{ss}$ would have been reduced from 127 mg m^{-3} to 52 mg m^{-3}, $[\overline{TP}_{epi}]_{ss}$ from 63 mg m^{-3} to 20 mg m^{-3}, and $[\overline{chl\ a}]_{ss}$ from 15 mg m^{-3} to 7.5 mg m^{-3}. As shown in Figure 9, this would represent a considerable improvement in quality at Skinner Lake. Considerations such as these, with lake-specific models, can focus attention of planners on management alternatives most likely to achieve the intended goals.

In summary, calibrating a general lake model for a single lake requires knowledge of the lake's specific hydrological and limnological variables. Total phosphorus loading for Skinner Lake was predominantly from inlet streams. Other sources, such as atmosphere and septic tanks,

had a negligible impact on relationships in the model. Flushing coefficients (ρ) during snowmelt and ice-off were > 1.0 at Skinner Lake in the years of this study. Coefficients in subsequent spring overturn periods were also > 1.0 . $[\overline{TP}_L]$ in the ice-free period was determined during the period of spring overturn just prior to stratification when $\rho = 1.0$. and continuing through the time of stratification. Other temperate zone lakes with high watershed area: lake area relationships may follow this pattern. Internal phosphorus loading influenced whole-lake [TP]. However, algal production in Skinner Lake was related to the [TP] of the epilimnion. $[\overline{TP}_{epi}]_{ss}$ was related to stream $[\overline{TP}_i]$ in the manner described by the Skinner-specific model. The addition of internal TP load to $[\overline{TP}_i]$ was not necessary in modeling the system. In other stratified, eutrophic lakes, similar considerations might be appropriate. Results of this study call attention to the need for site specific information on which to base cost-effective land management decisions.

Figure 9 shows an improvement in the condition of Skinner Lake between 1979 and 1982. Reduction in $[\overline{TP}_{stream}]_{ss}$, $[\overline{TP}_{epi}]_{ss}$ and $[\overline{chl\ a}]_{ss}$ occurred. This improvement was due to land management practices implemented on the watershed during 1978-1981, and/or to ordinary between-year variability in the systems. It should be noted that, by definition of variables in the Skinner Lake model, comparable portions of the water-year in 1979 and 1982 were used in this study. Between-year differences in rain events on the watershed, for example, differences in the intensity of individual events and associated differences in erosional runoff, were minimized in the model. The time interval over which $t_{w_{ss}}$ was calculated was nearly the same for both years, as was the value of $t_{w_{ss}}$ (0.63 in 1979 and 0.65 in 1982), and unusually intense storms did not occur in those intervals in either year. It is probable that land management was the primary cause for the improvement observed in Skinner Lake during this study. However, ordinary between-year variability was not measured in the system during years prior to land treatment, and only a continuing trend of improvement with maintenance of existing practices and implementation of others on the watershed in years ahead will confirm this.

Literature Cited

Allen, R.J. and B.C. Kenney. 1978. Rehabilitation of eutrophic Prarie lakes in Canada. Verh. Internat. Verein. Limnol. 20:214-224.

Barnes, B.S. 1940. Discussion of analysis of runoff characteristics by O.H. Meyer. Am. Soc. Civ. Engng. Trans. 105:1-106.

Batterson, T.R. and C.D. McNabb. 1983. Arsenic in Lake Lansing, Michigan. Environ. Toxicol. Chem. in press.

Chapin, J.D. and P.D. Uttormark. 1973. Atmospheric contributions of nitrogen and phosphorus. Tech. Rep. Wat. Resources Ctr. Univ. Wis., Madison. 35 pp.

Chapra, S. 1975. Comment on: "An empirical method of estimating the retention of phosphorus of lakes" by W.B. Kirchner and P.J. Dillon. Water Resour. Res. 11:1033-1034.

Chiaudani, G. and M. Vighi. 1974. The N:P ratio and tests with Selanastrum to predict eutrophication in lakes. Water Res. 8:1063-1069.

Christensen, R.G. and C.D. Wilson. 1976. Best management practices for non-point source pollution control. A report on a seminar. US EPA, Chicago, Illinois. 323 pp.

Dillon, P.J. 1974. A critical review of Vollenweider's nutrient budget model and other related models. Water Resources Bull. 10:969-989.

Dillon, P.J. 1975. The phosphorus budget of Cameron Lake, Ontario: the importance of flushing rate to the degree of eutrophy in lakes. Limnol. Oceanogr. 19:28-39.

Edmondson, W.T. 1961. Changes in Lake Washington following an increase in nutrient income. Verh. Internat. Verein. 14:167-175.

Clandon, R.P., F.C. Payne, C.D. McNabb and T.R. Batterson. 1981. A comparison of rain-related phosphorus and nitrogen loading from urban, wetland, and agricultural sources. Water Research. 15:881-887.

Hutchinson, G.E. 1957. A Treatise on Limnology. I. Geography, Physics and Chemistry. New York, John Wiley & Sons, Inc., 1015 pp.

Kirchner, W.B. and P.J. Dillon. 1975. An empirical method of estimating the retention of phosphorus in lakes. Water Resour. Res. 11:182-183.

Lake, J. and J. Morrison. 1977. Environmental impact of land use on water quality. Final Report on the Black Creek Project (Summary). U.S. Environmental Protection Agency, Chicago, Illinois. 94 pp.

Larsen, D.P. and H.T. Mercier. 1976. Phosphorus retention capacity of lakes. Jour. Fish. Res. Bd. Canada. 33:1742-1750.

McNabb, C.D., B.J. Premo, J.R. Craig and M. Siami. 1982. Project Report. A cooperative project to determine the effectiveness of land treatment in reducing the trophic state of Skinner Lake, Indiana. Submitted to Soil Conservation Service, Noble Co., Indiana.

Nurnberg, G.K. 1982. The prediction of internal phosphorus load in lakes with anoxic hypolimnia. A contribution to the Limnology Research Centre, McGill University, Montreal, Quebec, Canada.

OECD. 1982. Eutrophication of waters. Monitoring, Assessment and and Control. Technical Report ISBN. 92-64-12298-2, OECD, 2 rue Andre-Pascal, Paris. 154 pp.

Pearson, J. 1978. Fish management at Skinner Lake, Noble County Indiana. Indiana Department of Natural Resources. Division of Fish and Wildlife.

Rast, W. and F. Lee. 1978. Summary analysis of the North American OECD Program on eutrophication (U.S. Portion) U.S. Environmental Protection Agency 600/3-78-008. Ecol. Res. Ser. Corvallis, Oregon.

Rawson, D.S. 1955. Morphometry as a dominant factor in the productivity of large lakes. Verh. Internat. Verein. Limnol. 12:164-175.

Reckhow, K.H. 1977. Phosphorus models for lake management. Ph.D. dissertation. Harvard Univ., Cambridge, Mass. 304 pp.

Reckhow, K.H. 1981. Lake data analysis and nutrient budget modeling. U.S. Environmental Protection Agency, EPA-600/3-81-011. Corvallis, Oregon.

Sakamoto, M. 1966. Primary production by phytoplankton community in some Japanese lakes and its dependence on lake depth. Arch. Hydrobiol. 62:1-28.

Sawyer, C.N. 1947. Fertilization of lakes by agricultural and urban drainage. Jour. New Engl. Water Works Assoc. 61:109-127.

Smith, Val H., 1982. The nitrogen and phosphorus dependence of algal biomass in lakes: An empirical and theoretical analysis. Limnol. Oceanogr. 27:1101-1112.

Smith, V.H. and J. Shapiro. 1981. Chlorophyll-phosphorus relations in individual lakes. Their importance to lake restoration strategies. Environmental Science and Technology. 15(4):444-451.

Strickland, J.D.H. and T.R. Parsons. 1965. A manual of sea water analysis. 2nd edition. Fish. Res. Board, Ottawa, Canada.

U.S. Department of Interior Bureau of Reclamation. 1967. Water Measurement Manual. Denver, Colorado. 329 pp.

U.S. Environmental Protection Agency. 1971. Methods for Chemical Analyses of Water and Wastes. Environmental Monitoring and Support Laboratory Office of Research and Development. Cincinnati,OH.

U.S. Environmental Protection Agency. 1979a. Methods for Chemical Analyses of Water and Wastes. Environmental Monitoring and Support Laboratory Office of Research and Development. Cincinnati, Ohio.

Vollenweider, R.A. 1968. Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication, 192 p. Annex, 21 p; Bibliography, 61 pp. Rep. Organization for Economic Cooperation and Development, DAS/CSI/68.27, Paris.

Vollenweider, R.S. 1975. Input-output models with special reference to the phosphorus loading concept in limnology. Schweiz, Z. Hydrol., 37:53-83.

Vollenweider, R.A. 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. Mem Ist. Ital. Idrobiol., 33:53-83.

Vollenweider, R.A. and J.J. Kerekes, 1980. Background and summary results of the OECD cooperative program on eutrophication. p. 25-36. Proc. International Symposium on Inalnd Waters and Lake Restoration. U.S. Environmental Protection Agency. 440/5-81-010 Washington, D.C.

Walker, W.W., Jr. 1977. Some analytical methods applied to lake water quality problems. Ph.D. dissertation. Harvard University Cambridge, Mass. 528 pp.

Walker, W.W.,Jr. 1979. Use of hypolimnetic oxygen depletion rate as a trophic state index for lakes. Water Resour. Res. 15(6): 1463-1470.

Wetzel, R.G. 1975. Limnology. W.B. Sounders & Co., Philadelphia. 743 pp.

APPENDIX I

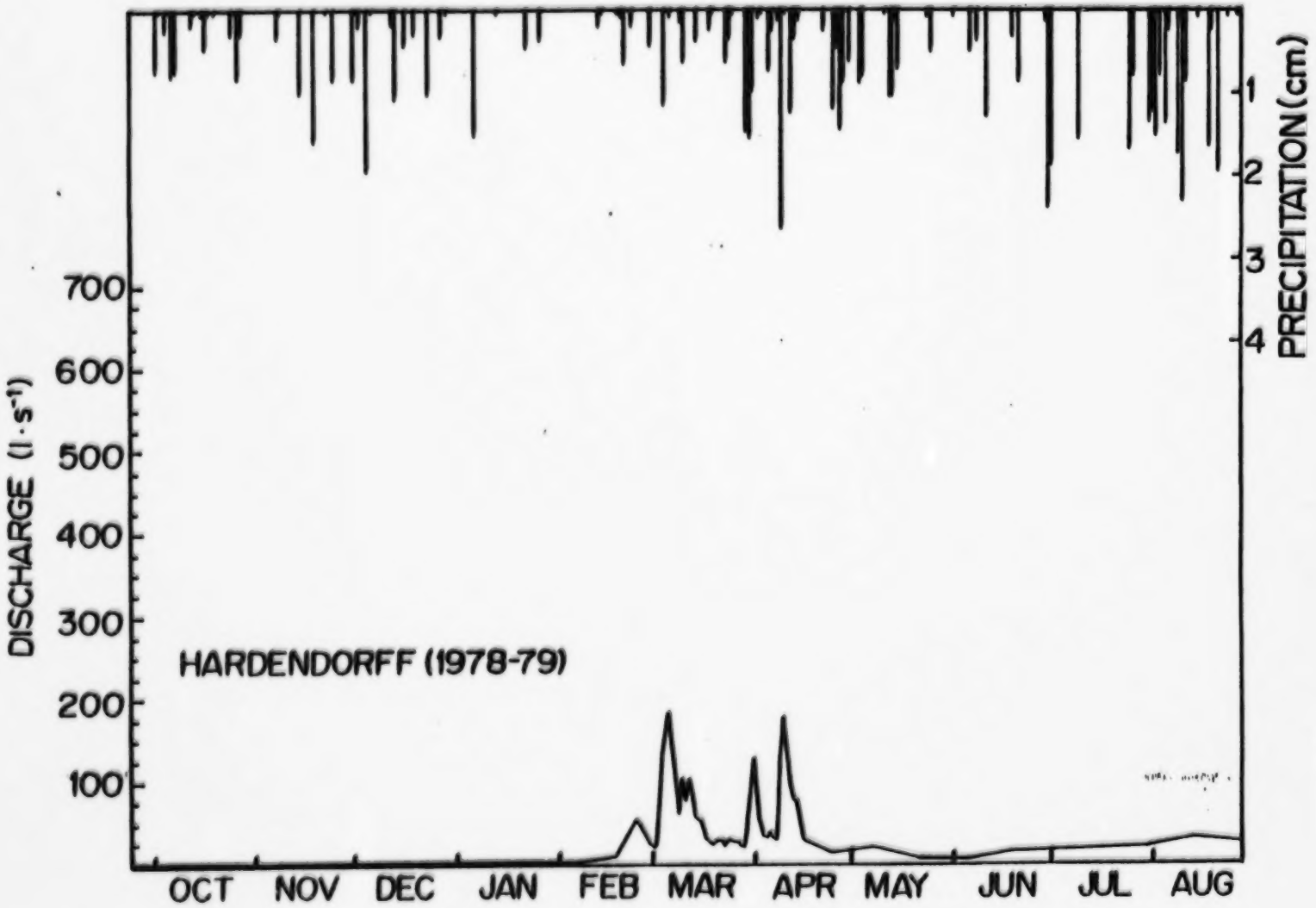

Figure A-1. Stream flow hydrograph and precipitation record for the Hardendorff inlet (1978-79).

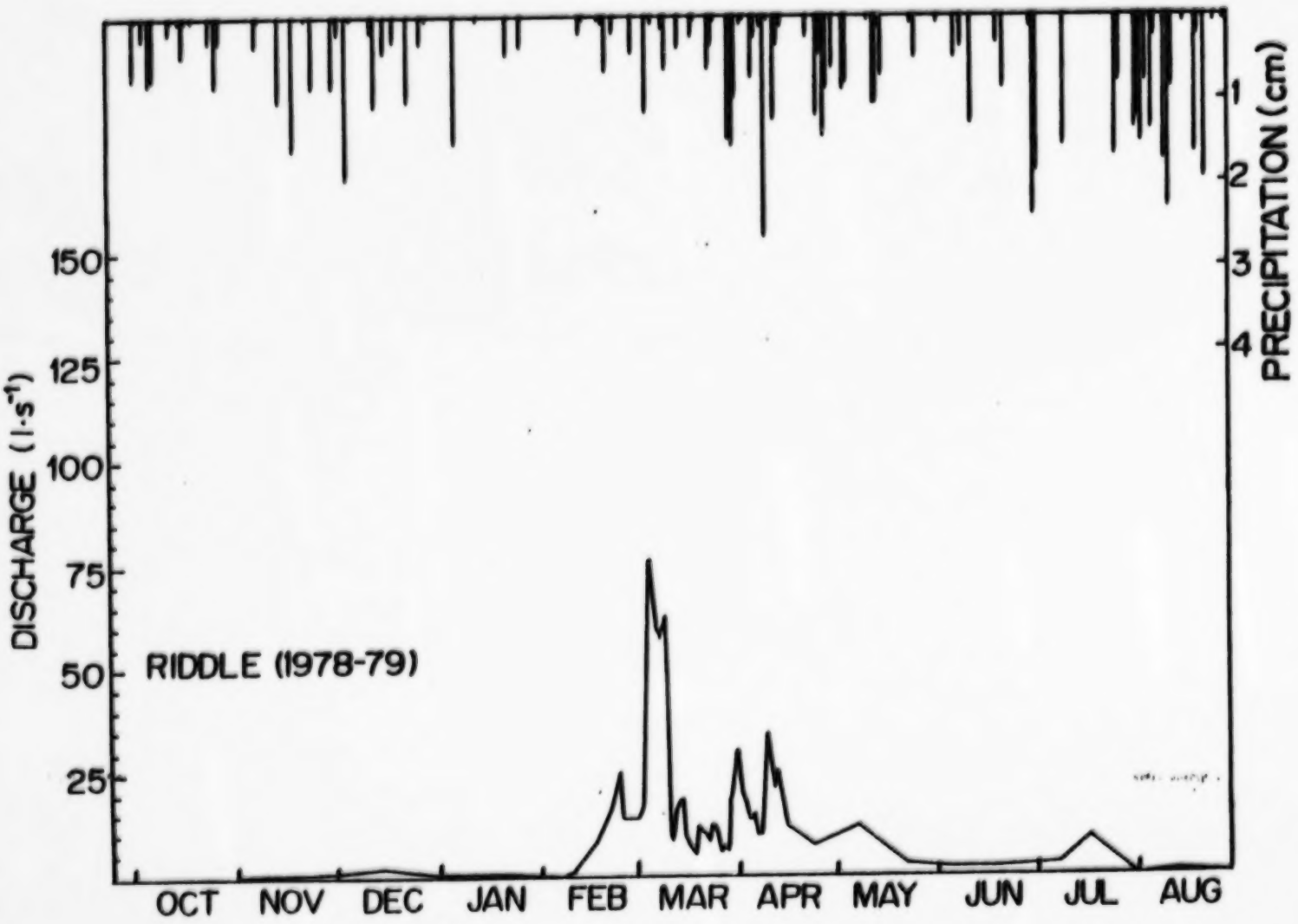

Figure A-2. Stream flow hydrograph and precipitation record for the Riddle inlet (1978-79).

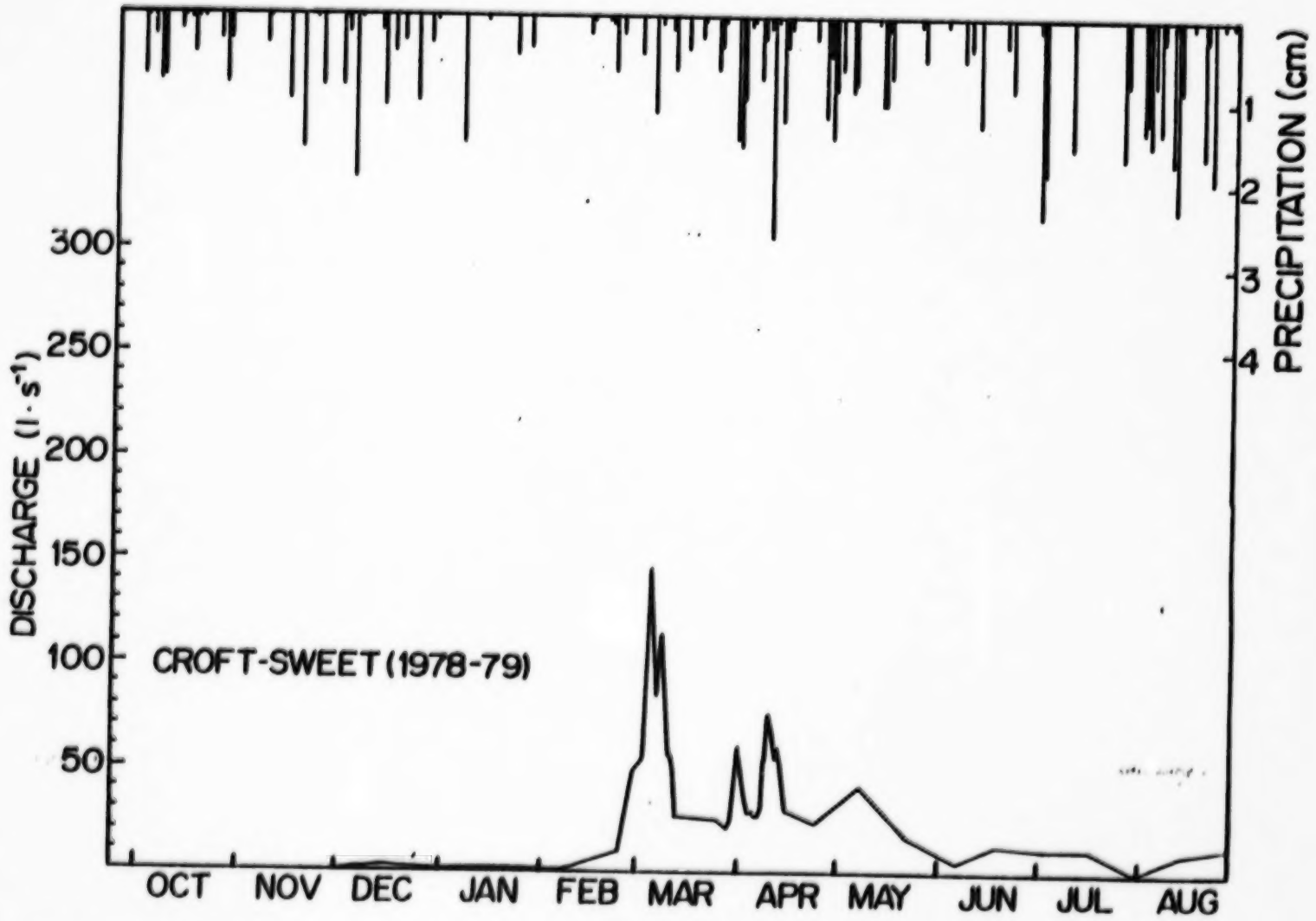

Figure A-3. Stream flow hydrograph and precipitation record for the Croft-Sweet inlet (1978-79).

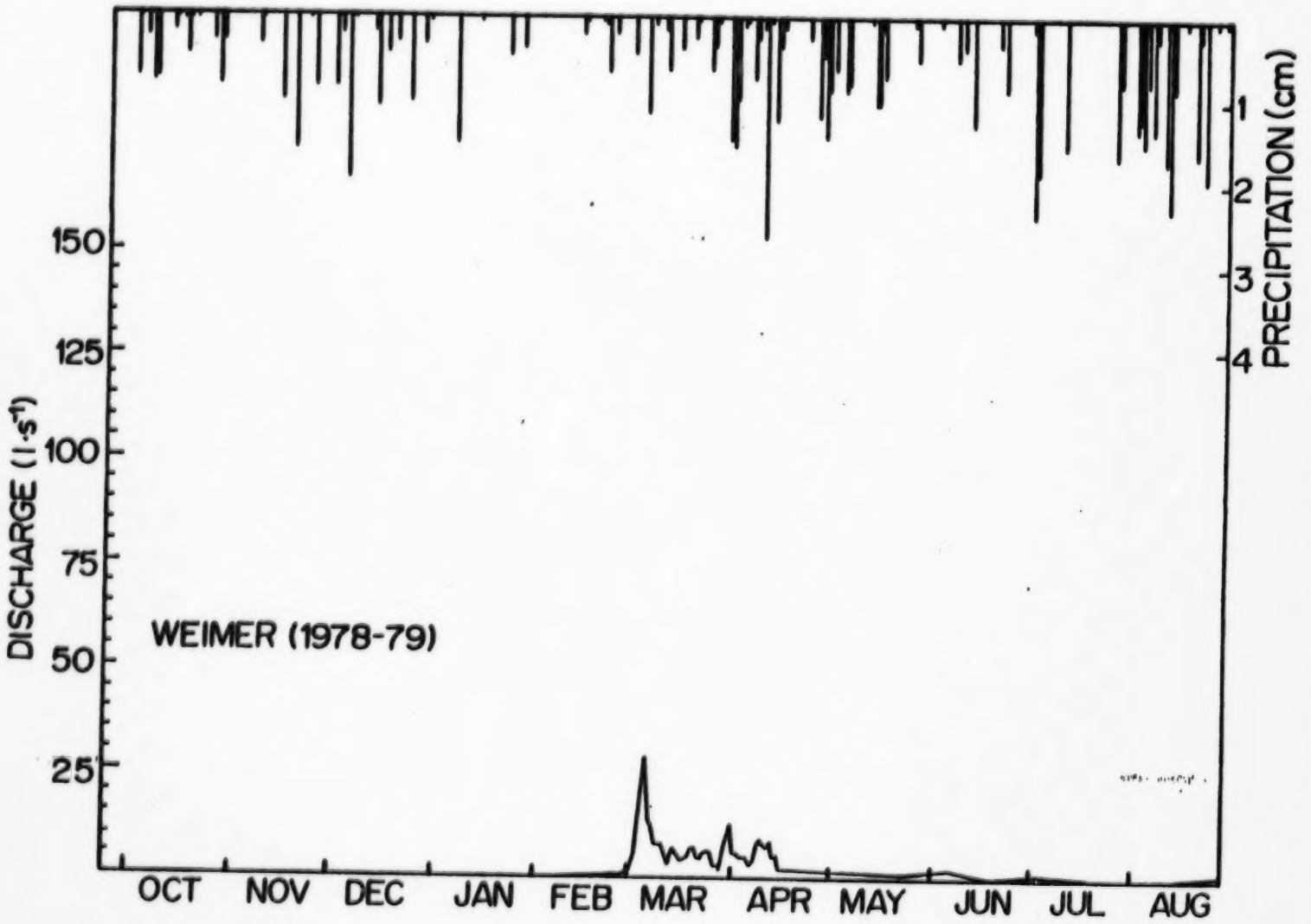

Figure A-4. Stream flow hydrograph and precipitation record for the Weimer inlet (1978-79).

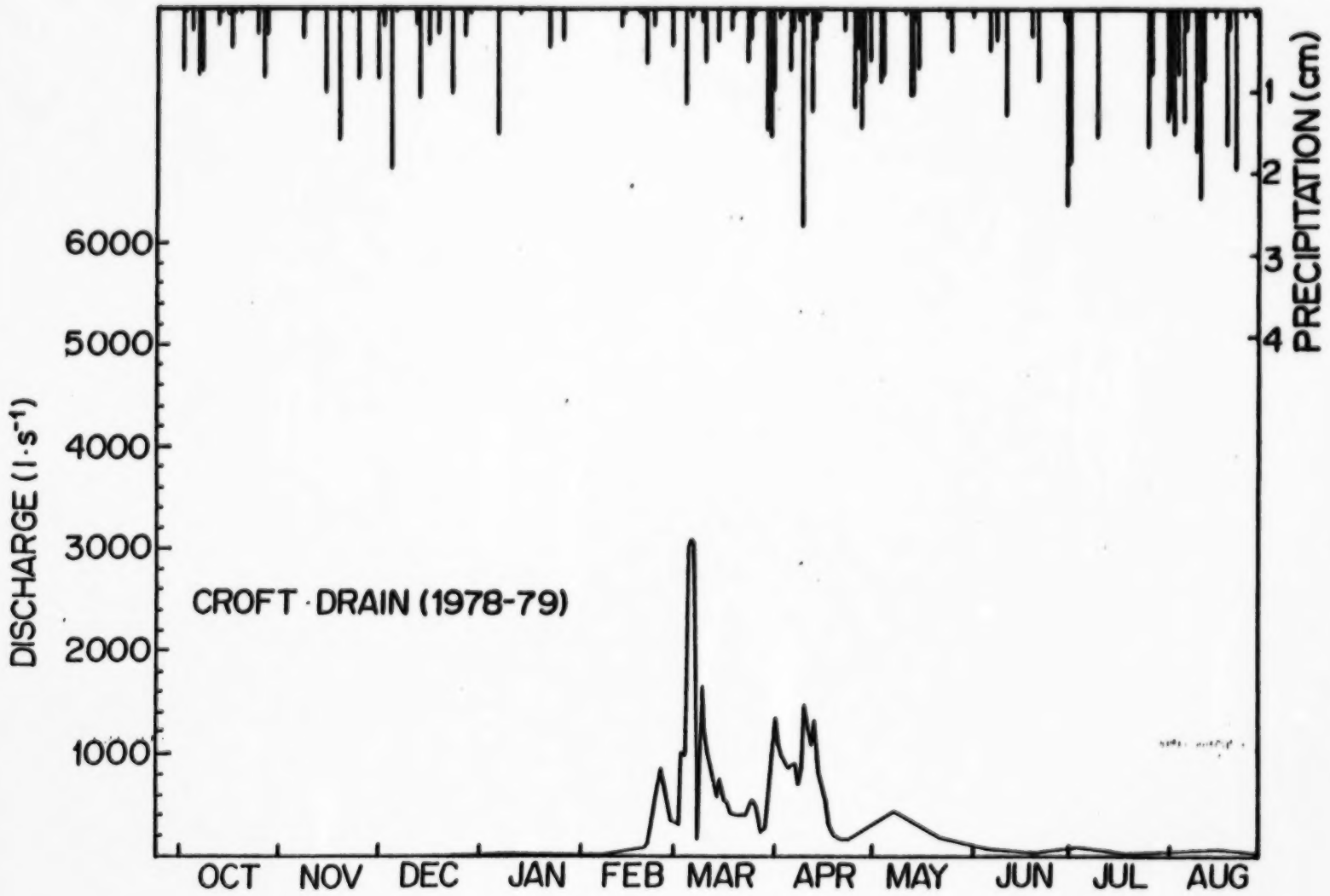

Figure A-5. Stream flow hydrograph and precipitation record for the Croft Drain (1978-79).

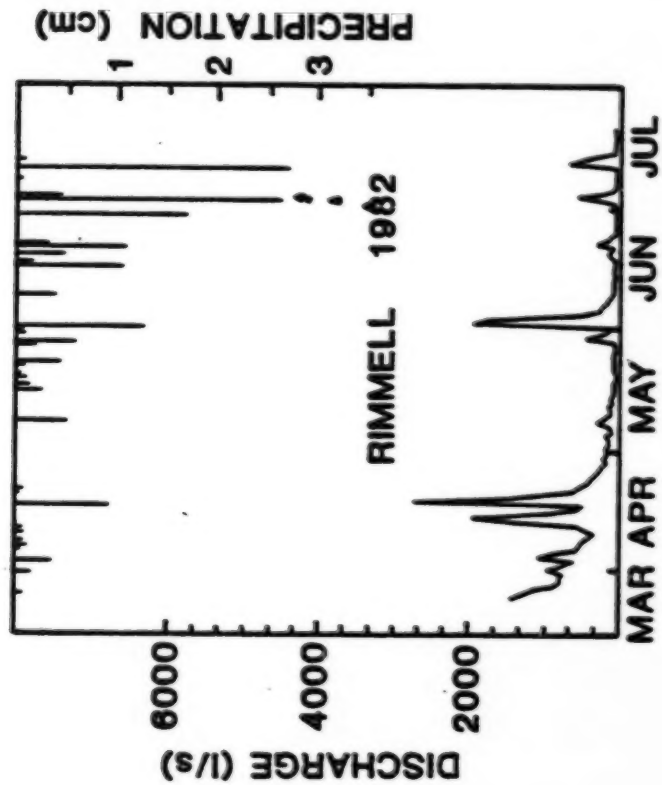

Figure A-6. Stream flow hydrograph and precipitation record for the Rimmell inlet (1982).

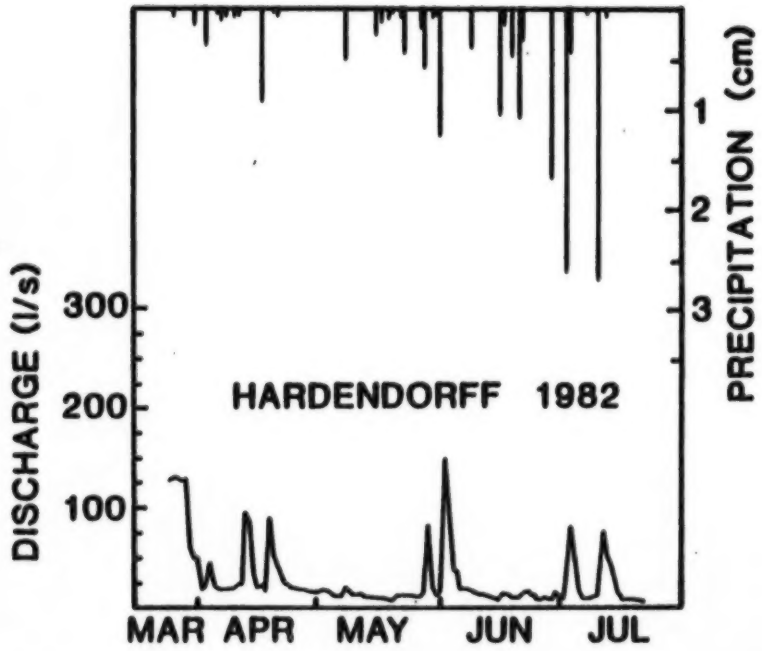

Figure A-7. Stream flow hydrograph and precipitation record for the Hardendorff inlet (1982).

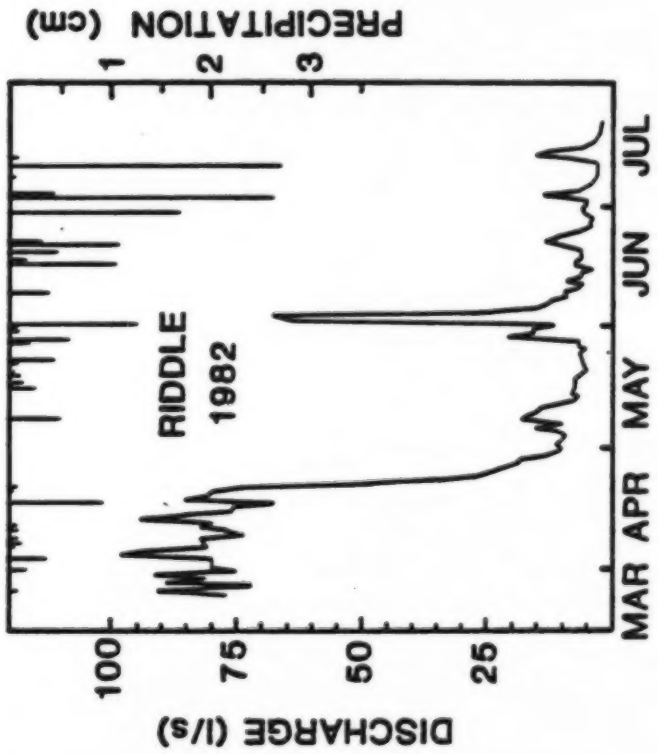

Figure A-8. Stream flow hydrograph and precipitation record for the Riddle inlet (1982).

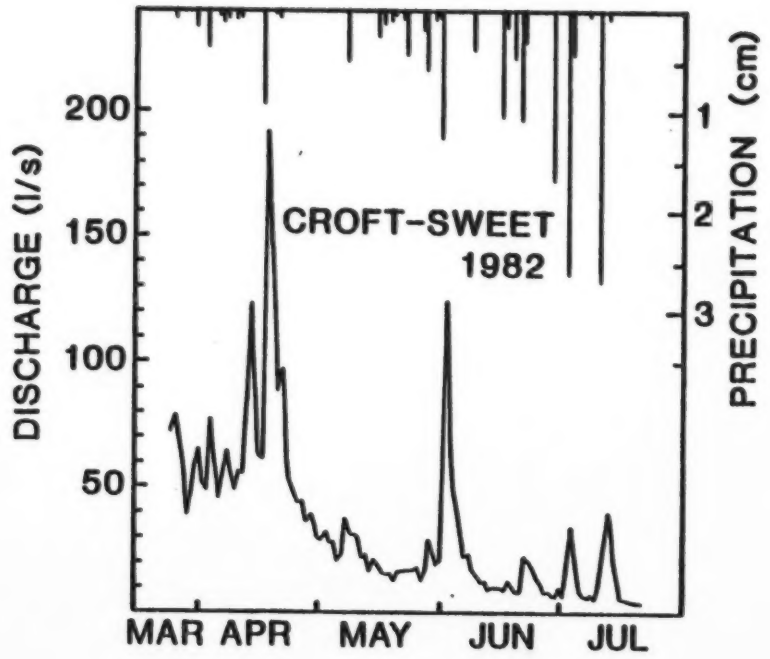

Figure A-9. Stream flow hydrograph and precipitation record for the Croft-Sweet inlet (1982).

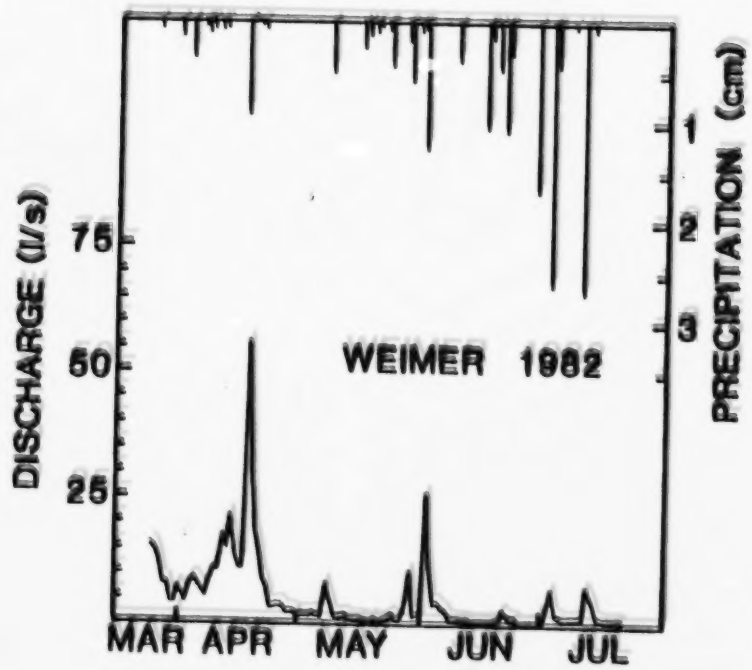

Figure A-10. Stream flow hydrograph and precipitation record for the Weimer inlet (1982).

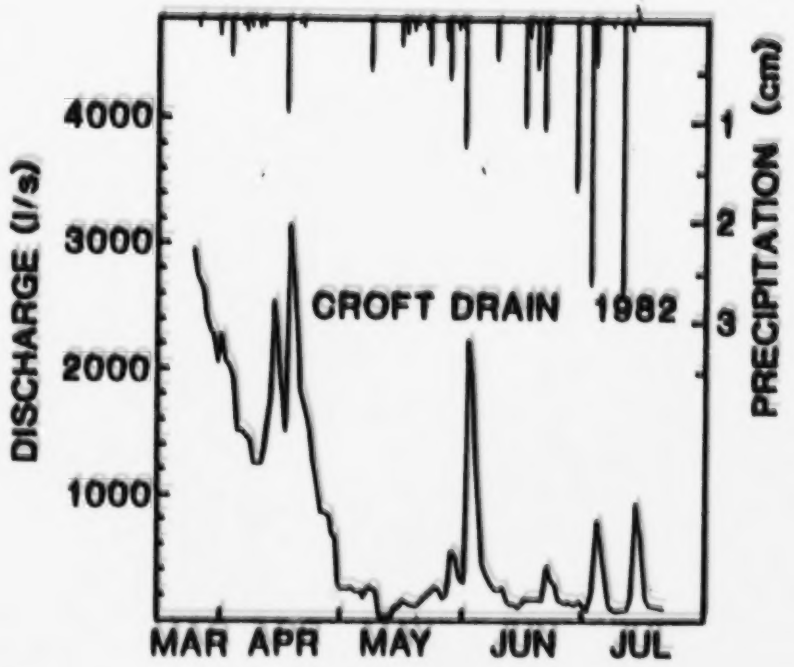

Figure A-11. Stream flow hydrograph and precipitation record for the Croft Drain (1982).

APPENDIX II

Table A-1. Estimated interval discharge (m^3) of inlet streams and outlet of Skinner Lake during 1978-79.

Interval	Rimmell	Hardendorff	Riddle	Weimer	Croft-Sweet	Croft Drain
9/6-10/16/78	15390	2278	2190	---[1]	---	---
10/17-11/6/78	12247	1088	1533	---	---	1814
11/7-11/27/78	23231	583	1783	---	583	10109
11/28-12/14/78	50576	1798	3812	---	5670	5119
12/25-1/16/79	19861	926	2322	---	4795	19764
1/16-2/6/79	8424	357	424	---	1908	16848
2/7-3/6/79	1795349	242993	161647	39356	190070	4086256
3/6-3/19/79	625905	57210	32729	10222	49628	1031825
3/20-4/1/79	637320	81303	25079	13725	51500	1018800
4/2-4/15/79	960220	82039	22105	7627	51916	1068400

	composited inlet discharge[2]	Croft Drain
4/15-4/23/79	226998	255517
4/24-5/7/79	308599	445435
5/8-5/21/79	82252	154072
5/22-6/5/79	66115	81219
6/6-6/18/79	74185	32405
6/19-7/2/79	84522	79532
7/3-7/16/79	85887	14971
7/17-7/30/79	76981	14215
7/31-8/13/79	123016	79230
8/14-8/27/79	135412	59726
8/28-9/17/79	100642	9872
9/18-10/3/79	92704	8750

1. Indicates no discharge during this time.
2. Discharge from all inlets was measured and added to gain the composite inlet discharge over these intervals.

Table A-2. Analytically determined [TP] (mg m^{-3}) in samples from inlet streams and outlet of Skinner Lake during 1978-79

Date	Rimmell	Hardendorff	Riddle	Weimer	Croft-Sweet	Croft Drain
9/6/78	255	106	.76	---[1]	---	---
10/16/78	72	100	76	---	---	---
11/6/78	65	128	37	---	---	54
11/27/78	83	144	57	---	23	54
12/14/78	63	106	46	---	23	39
1/16/79	71	88	52	---	104	32
2/6/79	132	34	43	---	49	31
3/6/79	228	527	667	107	237	241
3/19/79	153	147	125	31	68	199
4/1/79	132	194	127	48	72	117
4/15/79	177	274	229	68	122	93

	composited inlet sample[2]	Croft Drain
4/23/79	57	78
5/7/79	77	33
5/21/79	80	101
6/5/79	34	27
6/18/79	34	16
7/2/79	66	32
7/16/79	91	20
7/30/79	99	29
8/13/79	152	31
8/27/79	95	43
9/17/79	65	81
10/3/79	113	81

1. Indicates no discharge at this time.
2. Samples from all inlets were composited according to discharge and composite was analyzed for [TP].

Table A-3. Estimated interval discharge (m^3) of inlet streams and outlet of Skinner Lake during 1982.

Interval	Rimmell	Hardendorff	Riddle	Weimer	Croft-Sweet	Croft Drain
3/24 - 4/4/82	833138	70079	78438	7410	55759	2110455
4/5 - 4/19/82	1158640	59420	103770	21277	107253	2364740
4/20 - 5/3/82	372791	27346	36868	5537	60352	1655680
5/4 - 5/18/82	178226	16313	13819	2162	29871	191430
5/19 - 6/1/82	275665	31120	14194	3201	28359	322006
6/2 - 6/15/82	388139	29917	17469	2995	30078	379278
6/16 - 6/28/82	142632	13921	8022	328	14193	200168
6/29 - 7/13/82	282487	37179	18954	56	41674	372443
7/14 - 7/28/82	94162	12393	6318	---[1]	13891	137481
7/29 - 8/10/82	92428	3044	2788	---[1]	4823	69975

1. Indicates no discharge during this time.

Table A-4. Analytically determined [TP] (mg m^{-3}) in samples from inlet streams and outlet of Skinner Lake during 1982.

Date	Rimmell	Hardendorff	Riddle	Weimer	Croft-Sweet	Croft-Drain
3/24/82	230	132	204	52	122	166
4/4/82	274	110	174	46	88	136
4/19/82	242	313	161	72	82	119
5/3/82	56	81	83	17	58	78
5/18/82	53	59	64	50	45	35
6/1/82	288	182	166	74	59	63
6/15/82	62	40	97	64	74	34
6/28/82	113	44	66	50	42	25
7/13/82	60	220	202	40	95	65
7/28/82	101	58	58	---[1]	64	43
8/10/82	115	56	82	---[1]	45	30

1. Indicates no discharge at this time.